# Five Essays in Energy Economics

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The Faculty of Economics, Business Administration and Information Technology of the University of Zurich hereby authorises the printing of this Doctoral Thesis, without thereby giving any opinion on the views contained therein.

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# Preface

While writing my doctoral thesis at the Socioeconomic Institute I had the great privilege and pleasure to enjoy the help and support of several people.

First and foremost, I am thankful to Prof. Dr. Peter Zweifel, my thesis supervisor, who encouraged me to do research in energy economics. His guidance, support, and intellectual curiosity have been greatly inspiring and most valuable throughout my entire doctoral studies at the University of Zurich.

In addition, I would like to thank Prof. Dr. Reinhard Madlener, my thesis co-supervisor, for several great discussions, useful comments and suggestions to improve my research. I am also indebted to Prof. Dr. Massimo Filippini and Dr. Mehdi Farsi, who introduced me to the exciting field of efficiency analysis.

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My parents have supported me throughout my thesis and I greatly value the many debates that I had with my father about socialism, labour unions, and the free market. However, this thesis never would have been finished (in fact, it never would have even started) without the wonderful support and encouragement of my girlfriend Cornelia Schaerer. During times of great challenges she always managed to make me smile and to carry on.

# Contents

# Chapter 1

# Introduction

The following five essays investigate topical issues related to energy economics. Chapters 2 and 3 present empirical studies to determine efficient electricity-generating portfolios in the United States and Switzerland for the year 2003. Two different types of real asset portfolio holders will be considered, viz. current user (Chapter 2) and investor (Chapter 3). Chapter 4 assesses the current impact of liberalization on the scope for efficiency improvement in electricity-generating portfolios for the United States and Switzerland; while chapter 5 explores which future electricity-generating technologies seem most promising to be part of an efficient portfolio for Switzerland, using predicted data from 2005 to 2035. Chapter 6 outlines a game-theoretic analysis, modeling a gas transit game for Russia. Chapter 7 concludes.

The first four essays are based on Markowitz mean-variance portfolio theory (1952), where the variances (standard deviations), covariances, and expected returns of electricity-generating technologies are calculated to construct efficient portfolios. An efficient portfolio does not create unnecessary risk for a given expected return or, put the other way around, it maximizes the expected return for a given amount of risk. As stated by Fabozzi et al. (2002), portfolio theory is still the major instrument for constructing efficient portfolios for financial assets. According to Jansen et al. (2006), the first application of Markowitz mean-variance portfolio theory to energy is due to Bar-Lev and Katz (1976), who examined the efficiency of U.S. power utility companies. However, it took almost 30 more years until that subject became an issue for countries in Western Europe (see for example Awerbuch and Berger, 2003). One key contribution of the first four essays concerns the econometric procedure. Since shocks in generation costs per kWh (the inverse of expected returns) are correlated, seemingly unrelated regression estimation (SURE) is applied throughout to filter out the systematic components of the covariance matrix. The fifth essay purports to determine the bargaining power of Russia, Ukraine, and Belarus when negotiating transit fees, taking account of new projects such as the Northern European Gas

Pipeline (NEGP). After the collapse of the Soviet Union, newly independent states became indispensible parts of the Eurasian gas chain, causing a dramatic change for Russia, which now has to negotiate with third parties to agree on transit fees. This contribution predicts possible coalitions amongst the three countries, where estimated payoffs allow to determine whether co-operation or independent optimization is the dominant strategy. The following paragraphs provide some more detail about each individual chapter.

In Chapter 2 mean-variance portfolio theory is applied to power technologies of the United States and Switzerland adopting a current user view (here expected return is defined as kWh/USD in levels). Since some of the portfolios of particular interest (minimum variance, maximum expected return) call for a high share of one technology, security of supply becomes an issue. Shannon-Wiener and Herfindahl-Hirschman indices are calculated to see the trade-off between efficiency and security of supply. Results suggest that risk-averse utilities (and ultimately, consumers) in the United States would have gained from adopting a feasible portfolio containing more *Coal*, *Gas* and *Oil* at a price of a somewhat reduced security of supply. In the case of Switzerland, the realistic portfolio consists of *Nuclear*, *Storage hydro*, *Run of river* and *Solar,* with shares identical to those of the actual portfolio in 2003. Therefore, the current mix of Swiss generating technologies in Switzerland may be deemed efficient.

A current user is interested in the absolute value of expected returns of an electricity-generating portfolio. For example, a technology mix that promises to generate 7 kWh/USD electricity is preferred to one that offers 3 kWh/USD. By way of contrast, an investor usually does not care whether a portfolio mix of technologies costs USD 10 million or USD 500 million, as long as the expected return (measured in KWh/USD, say) increases in value over time. Depending on which view is adopted, different efficient portfolio recommendations may result.

Chapter 3 therefore complements the analysis presented in chapter 2 by adopting an investor view (here expected return is defined as changes of kWh/USD) and applies financial portfolio theory to determine efficient electricity-generating technology portfolios for the United States and Switzerland. The actual portfolio in 2003 contains *Coal, Nuclear*, *Gas*, *Oil*, and *Wind* in the case of the United States, and *Nuclear*, *Storage hydro*, *Run of river*, and *Solar* in the case of Switzerland, a country without domestic supplies of fossil fuels. Results suggest that as of 2003, the feasible maximum expected return (MER) electricity portfolio for the United States contains more *Coal*, *Nuclear*, and *Wind* than actual but markedly less *Gas* and *Oil*. By way of contrast, the minimum variance (MV) portfolio combines markedly more *Oil*, *Coal*, *Nuclear*, and *Wind* but almost no *Gas*. Therefore, regardless of the choice between MER and MV, U.S. utilities as investors are substantially inside the efficient frontier. This is even more true of their Swiss counterparts, likely due to continuing regulation of electricity markets, which is the subject of analysis in the next chapter.

In Chapter 4, both an investor (focused on changes in return) and a current user (focused on return in levels) view are adopted to determine efficient frontiers of electricity generation technologies in terms of expected return and risk as of 2003 for the United States and Switzerland. Here, results suggest that risk-averse investors and risk-neutral current users in the United States are considerably closer to their efficient frontier than their Swiss counterparts. As will be argued in this chapter, this is arguably due to earlier and more thorough deregulation of electricity markets in the United States.

Chapter 5 uses Markowitz mean-variance portfolio theory with forecasted data for the years 2005 to 2035 to determine efficient future electricity-generating technology mixes for Switzerland. In contrast to preceding chapters, additional generating technologies are included that are expected to be in use by 2035 but which have not been part of the generation mix in the year 2000. Results indicate that risk-averse electricity users in 2035 gain in terms of higher expected return, less risk, more security of supply and a higher return-to-risk ratio compared to 2000 by adopting a feasible minimum variance (MV) technology mix containing 28 percent *Gas*, 20 percent *Run of river*, 13 percent *Storage hydro*, 9 percent *Nuclear*, and 5 percent each of *Solar*, *Smallhydro*, *Wind*, *Biomass*, *Incineration*, and *Biogas* respectively. However, this mix comes at the cost of higher $CO_2$ emissions.

Chapter 6 departs from Markowitz mean-variance portfolio analysis but stays in the field of applied energy economics. The essay presented in this chapter deals with gas transition from Russia to Western Europe. Since the fall of the Soviet Union, Russia must somehow form a coalition with at least one of the transit countries Belarus and Ukraine in order to be able to ship gas to Western Europe. In modeling the gas transit game, this contribution accordingly contains a cooperative module serving to determine the bargaining power of the three countries, which depends on the coalition achieved. In the non-cooperative module, the three countries involved decide whether to cooperate or not, with Russia using side payments to induce cooperation. Using published demand and cost estimates, the predicted Nash equilibrium is the cooperative one resulting in the grand coalition. Predicted gas quantities correspond quite closely to actual 2004 and forecasted 2010 and 2030 figures. The completion of the North European Gas Pipeline (NEGP), a direct pipeline between Russia and Germany through the Baltic Sea, will benefit Russia decisively, to the detriment particularly of Ukraine.

Note that Peter Zweifel co-authored chapters 2-4 and Sandro Schirillo co-authored chapter 6. While the undersigned author was at least equally responsible for the intellectual inputs of chapters 2-4, the main contribution to chapter 6 is by Peter Zweifel. Chapter 2 appears 2009 in:

Analytical Methods for Energy Diversity – Mean-Variance Optimization for Electric Utilitities. Energy Policy and Economics Series, Elsevier (refereed). Chapter 3 has been submitted to the *Energy Economics*. Chapter 4 appears in the *Zeitschrift für Energiewirtschaft* (refereed). Chapter 5 will be submitted to an energy economics journal soon, and Chapter 6 has been submitted to the *Journal of Resource and Energy Economics*. During his Ph.D. studies the undersigned author also contributed to: Zweifel, Peter, Boris Krey and Maurizio Tagli (2006). Private Voluntary Health Insurance in Developing Countries: Friend or Foe? Chapter Three: Supply of Private Voluntary Health Insurance in Low-Income Countries, World Bank, Washington D.C. But since this contribution has nothing in common with energy economics, the undersigned author decided not to include this study in his thesis.

Boris Krey
Bassersdorf, August 2008

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# Efficient and Secure Power for the United States and Switzerland

**Boris Krey and Peter Zweifel*** †

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# Chapter 2

# Efficient and Secure Power for the United States and Switzerland

## 2.1 Introduction

Efficient portfolios of assets maximize expected return for any given level of risk or alternatively minimize expected risk for every level of expected return. This founding concept of finance, developed by Markowitz (1952), can be applied to a portfolio of real assets as well. Power companies, holding a portfolio of power generation technologies, face the task of achieving maximum expected return (defined as kWh/U.S.$[1]) for any given level of risk (defined as the standard deviation of expected return), or put the other way around, the minimum risk for every level of expected return in terms of kWh/U.S.$. In this way, they contribute to the attainment of widely recognized objectives of energy policy, viz. the provision of electricity in an economical way while minimizing the overall risk of cost variability. This calls for taking into account the correlations between costs and therefore expected returns [2] of different power generation technologies.

For example, fossil fuel-generated electricity faced dramatic cost fluctuations during the past decade, mainly caused by a oil price surge exceeding 300 percent[3] since 1999. In contrast, power generated by storage hydro fluctuated by less than 5 percent in Switzerland, mainly because of a stable price of water use. A portfolio containing both generation technologies therefore reduces risk considerably. Indeed, portfolio mixes in 2003 containing a larger share of gas power (for the United States) and the same share of nuclear (for Switzerland), combined with new-renewable

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[1] The definition of expected return adopted in this study is similar to Awerbuch (2004), who used the definition kWh/cents.

[2] As outlined in Awerbuch (2006b) and Awerbuch and Berger (2003), generation cost is nothing but the inverse of expected return. Therefore results are unaffected by whether portfolio optimization is based on maximizing expected return or minimizing cost, both ways leading to the same outcome.

[3] Source: WTRG Economics (www.wtrg.com)

generation technologies such as wind (for the United States) and solar (for Switzerland) serve to greatly increase expected returns for both countries while keeping risk more or less constant. However, this concentration on mainly two technologies implies a reliance on two primary energy sources, which may jeopardize security of supply.

Apart from containing an international comparison, the present contribution has three novel features. First, while most of the published research adopts the investor's point of view that characterizes financial analysis, this work takes the current user's point of view. For financial investors, the current price of a share is irrelevant for the composition of their portfolio. All that counts is its future increase in value. By way of contrast, a utility must consider the current cost per kWh of the inputs it intends to use. Second, correlations between unobserved shocks influencing the cost of electricity generation technologies (the inverse of expected return) are taken into account, improving the efficiency of estimates. This clearly differs from previous contributions, where these correlations are not accounted for. Third, the security of supply issue is also addressed. Indeed, an efficient portfolio of electricity generation technologies may call for a high share of one particular technology (and hence energy source) if unit costs are strongly correlated, obviating diversification effects. However, such a solution would be deemed to impart excessive risk to the provision of electricity in the eyes of most policy makers. To reflect this concern, indices of concentration are calculated in order to depict a possible tradeoff between efficiency and security of supply with regard to electricity generation technologies.

This study is structured as follows. Section 2.2 presents a short review of key literature on portfolio theory as applied to power generation technologies and on the measurement of supply security. In section 2.3, the theory of efficient power generation portfolios from a current user's point of view is laid out. Because common shocks (such as weather) impinge on generation costs (the inverse of expected return) seemingly unrelated regression estimation method is adopted. In section 2.4, SURE-based efficient frontiers are constructed for the United States and Switzerland, with emphasis on solutions with special features, i.e. minimum variance (MV), same expected return (SER), same variance (SV), and maximum expected return (MER) portfolios. Shannon-Wiener and Herfindahl-Hirschman indices will also be calculated to see whether U.S. and Swiss power generation technologies are sufficiently diversified. Conclusions are offered in section 2.5.

## 2.2 Literature review

Portfolio theory and the concept of diversification were introduced by Markowitz (1952). Efficient portfolios maximize expected return for a given amount of risk (which is measured by the variance or standard deviation of the return of the portfolio). Equivalently, they minimize risk for a given expected return. As stated by Fabozzi et al. (2002), portfolio theory continues to be the most important tool for constructing efficient portfolios for financial assets.

More recently, portfolio theory has also been applied to real assets, such as those related to energy generation. According to Jansen et al. (2006), the first application to energy is due to Bar-Lev and Katz (1976), who examined whether U.S. power utility companies are efficient users of fossil fuel. Costs of inputs are "as burned", including overheads resulting from transportation expenses, heating of oil lines, stock cleaning, and fuel handling facilities for coal, fuel storage, inventory, and maintenance. Compared to the efficient frontier, actual operations by electric utilities are characterized by a relatively high rate of expected returns, combined with an excessive amount of risk however. The authors argue that utilities could move towards the efficient frontier by purchasing fuels at a higher but guaranteed (i.e. futures market) price.

Adegbulugbe et al. (1989) examine the long-term optimal structure of energy supply in Nigeria. They use a multiperiod linear programming model of the total energy system to minimize direct fuel costs while achieving certain developmental objectives. Results indicate that gas and petroleum should play an important role in the future Nigerian energy mix, with coal limited to a very small share as long as its costs of production and transportation are as high as they were at the time. Nuclear power and solar energy are not part of the efficient frontier at all.

A major limitation characterizing the contributions of both Bar-Lev and Katz (1976) and Adegbulugbe et al. (1989) is that they fail to account for time-varying covariances in energy prices. In addition, they neglect possible correlations between shocks impinging on primary energy prices. Finally, only the unit costs of fuels enter calculations, causing other private costs (current operation, use of capital) to be disregarded, let alone social costs (health and global warming).

Humphreys and McClain (1998) tackle at least three previous limitations by (i) filtering out the systematic components of the covariance matrix of energy prices over time, (ii) using a more comprehensive definition of private cost, and by (iii) including external costs. As to (i), their estimated variances and covariances are derived from so-called Generalized Autoregressive Conditional Heteroscedastic (GARCH) models. By applying GARCH, the authors try to filter out systematic changes in volatility in response to shocks. Their results suggest that a shift away from oil towards natural gas would reduce overall volatility at a given rate of expected return (in terms of reduced cost of power). Focusing on changes rather than levels, Humphreys and McClain adopt the conventional financial portfolio approach, i.e. the investor's point of view. However, producers are mainly interested in the level of prices they have to pay for their inputs, with expected future changes being of secondary importance. Finally, as is true of all other studies, the authors fail to control for unobserved shocks affecting several generation technologies at the same time.

More recently, there has been research singling out electricity. Berger et al. (2003) use Markowitz theory to examine existing and projected generation technology mixes in the European Union. According to their study, renewables that are characterized by high fixed but low variable costs (such as wind) figure prominently in efficient portfolios both due to their favorable expected returns and diversification effects. A weakness of this study is its data base. Important components of cost are proxied by business indicators such as the S&P 500 index. In addition, neither external costs nor common unobserved shocks are taken into account.

Roques et al. (2006, 2005) apply stochastic optimization to determine whether nuclear power may serve as a hedge against uncertain gas and carbon prices. However, high and uncertain capital cost as well as potential construction and licensing delays cause the role of nuclear to be limited. Rather than estimating correlations between unit costs, the authors resort to the use of arbitrary correlation scenarios. This arbitrariness is crucial because the stronger the (positive) correlation between the cost of nuclear power and other technologies, the weaker its diversification effect.

Jansen et al. (2006) again apply Markowitz theory to determine efficient portfolios of power-generating technologies for the Netherlands in the year 2030. Their results suggest that diversification may yield a risk reduction of up to 20 percent at no extra loss in expected returns.

Portfolio analysis assumes shocks to be stochastic. However, cost hikes may be the result of concerted behavior on the part of suppliers who have market power. The risk of collusion is the higher the smaller the number of suppliers, which in turn varies directly with the number of energy sources. Based on this line of argument, measures of concentration such as the Shannon-Wiener (*SW*) and Herfindahl-Hirschman (*HH*) indices have been increasingly applied in studies related to power generation technologies. The *SW* index (a measure of entropy) reflects diversity, while the *HH* index measures market concentration. Both indices permit to evaluate the security of supply of different power generating technologies thanks to a greater number of suppliers. They therefore complement the mean-variance portfolio approach for policy makers who fear purchases of primary energy to be exposed to collusion or monopoly – a consideration of relevance especially in the markets for natural gas and uranium.

Grubb et al. (2005) explore the relationship between low-carbon objectives and strategic security of supplies in the context of the UK power system by calculating both *SW* and *HH* indices. They identify a complementarity between the two objectives in that a reduction of carbon intensity is uniformly associated with greater long-term diversity in UK power generation.

However, they neglect stochastic shocks altogether, which could cause a tradeoff between Markowitz efficiency and protection from market power.

Doherty et al. (2005) complement their portfolio analysis with the *SW* index to assess the fuel portfolio of a power plant in Ireland as of 2020. Not surprisingly, the plant's efficient minimum variance portfolio contains a much more diversified mix of generation technologies than the maximum expected return portfolio, while the *SW* index favors the minimum variance alternative. However, this study is based on a covariance matrix of returns that has not been purged of extreme shocks and therefore may lack stability.

## 2.3 Methodology

### 2.3.1 Real asset portfolio estimation

Owners of a real asset portfolio seek to maximize its expected return at a given risk or alternatively to minimize risk given their expected return. In more formal terms, the expected return of a real asset portfolio $E(\mathrm{R}_p)$ consisting of $m$ risky assets is given by

$$E(\mathrm{R}_p) = \sum_{i=1}^{m} w_i E(\mathrm{R}_i), \tag{1}$$

where $w_i$ is the share of asset $i$ and $E(\mathrm{R}_i)$ its expected return. In the present case of five components, the portfolio standard deviation ($\sigma_p$) involves the variances and correlation coefficients in the following way,

$$\sigma_p = \begin{pmatrix} w_1^2\sigma_1^2 + w_2^2\sigma_2^2 + w_3^2\sigma_3^2 + w_4^2\sigma_4^2 + w_5^2\sigma_5^2 + 2w_1w_2\rho_{12}\sigma_1\sigma_2 \\ + 2w_1w_3\rho_{13}\sigma_1\sigma_3 + 2w_1w_4\rho_{14}\sigma_1\sigma_4 + 2w_1w_5\rho_{15}\sigma_1\sigma_5 + 2w_2w_3\rho_{23}\sigma_2\sigma_3 \\ + 2w_2w_4\rho_{24}\sigma_2\sigma_4 + 2w_2w_5\rho_{25}\sigma_2\sigma_5 + 2w_3w_4\rho_{34}\sigma_3\sigma_4 + 2w_3w_5\rho_{35}\sigma_3\sigma_5 \\ + 2w_4w_5\rho_{45}\sigma_4\sigma_5 \end{pmatrix}^{\frac{1}{2}}, \tag{2}$$

where $\rho_{ij} = \mathrm{cov}_{ij}/(\sigma_i\sigma_j)$, $i,j = 1,\ldots,5$, are correlation coefficients and $\sigma_i$ are individual standard deviations. In the case of the United States, the five sources are *Oil*, *Coal*, *Gas*, *Nuclear*, and *Wind*. Accordingly, eqs. (1) and (2) become

$$E(\mathrm{R}_{USp}) = w_{Oil}E(\mathrm{R}_{Oil}) + w_{Coal}E(\mathrm{R}_{Coal}) + w_{Gas}E(\mathrm{R}_{Gas}) + w_{Nuclear}E(\mathrm{R}_{Nuclear}) + w_{Wind}E(\mathrm{R}_{Wind}); \tag{3}$$

$$\sigma_p = \begin{pmatrix} w_{Oil}^2\sigma_{Oil}^2 + w_{Coal}^2\sigma_{Coal}^2 + w_{Gas}^2\sigma_{Gas}^2 + w_{Nuclear}^2\sigma_{Nuclear}^2 + w_{Wind}^2\sigma_{Wind}^2 \\ + 2w_{Oil}w_{Coal}\rho_{Oil,Coal}\sigma_{Oil}\sigma_{Coal} + 2w_{Oil}w_{Gas}\rho_{Oil,Gas}\sigma_{Oil}\sigma_{Gas} \\ + 2w_{Oil}w_{Nuclear}\rho_{Oil,Nuclear}\sigma_{Oil}\sigma_{Nuclear} + 2w_{Oil}w_{Wind}\rho_{Oil,Wind}\sigma_{Oil}\sigma_{Wind} \\ + 2w_{Coal}w_{Gas}\rho_{Coal,Gas}\sigma_{Coal}\sigma_{Gas} + 2w_{Coal}w_{Nuclear}\rho_{Coal,Nuclear}\sigma_{Coal},\sigma_{Nuclear} \\ + 2w_{Coal},w_{Wind}\rho_{Coal,Wind}\sigma_{Coal}\sigma_{Wind} + 2w_{Gas}w_{Nuclear}\rho_{Gas,Nuclear}\sigma_{Gas}\sigma_{Nuclear} \\ + 2w_{Gas}w_{Wind}\rho_{Gas,Wind}\sigma_{Gas}\sigma_{Wind} + 2w_{Nuclear}w_{Wind}\rho_{Nuclear,Wind}\sigma_{Nuclear}\sigma_{Wind} \end{pmatrix}^{\frac{1}{2}}. \quad (4)$$

Portfolio theory does not determine a single best mix but an efficient frontier containing an infinite number of solutions. The optimal solution depends on consumer preferences, which reflect risk aversion. In Figure 1, let there be only two generation technologies, GT1 and GT2. By assumption, GT1 (e.g. *Solar* generated power) has low expected return (measured as kWh/U.S.$) but low volatility of unit cost. By way of contrast, GT2 has much higher expected return but is more risky (e.g. *Run of river* generated power). If the correlation between the two generation technologies is less than perfect, the efficient frontier runs concave. The lower the correlation coefficient, the stronger this portfolio effect[4]. In Figure 1, the efficient frontier formed by GT1 and GT2 with its high expected return but also high volatility runs concave rather than linear, permitting holders of this power portfolio to profit from a diversification effect (Awerbuch and Berger, 2003). Although adding GT3 may not look attractive at first due to low expected returns, this technology is so little correlated with GT1 and especially GT2 that it causes the efficient frontier to become more concave. One example of this effect can be found in Awerbuch (2006a), who shows that by adding risky *Wind* generation to the existing power mix of Scotland, a substantially reduced portfolio standard deviation can be attained. Indeed, *Wind* generation costs in Scotland do not correlate with fossil prices, causing it to have a marked diversification effect (Awerbuch, 2006a)[5].

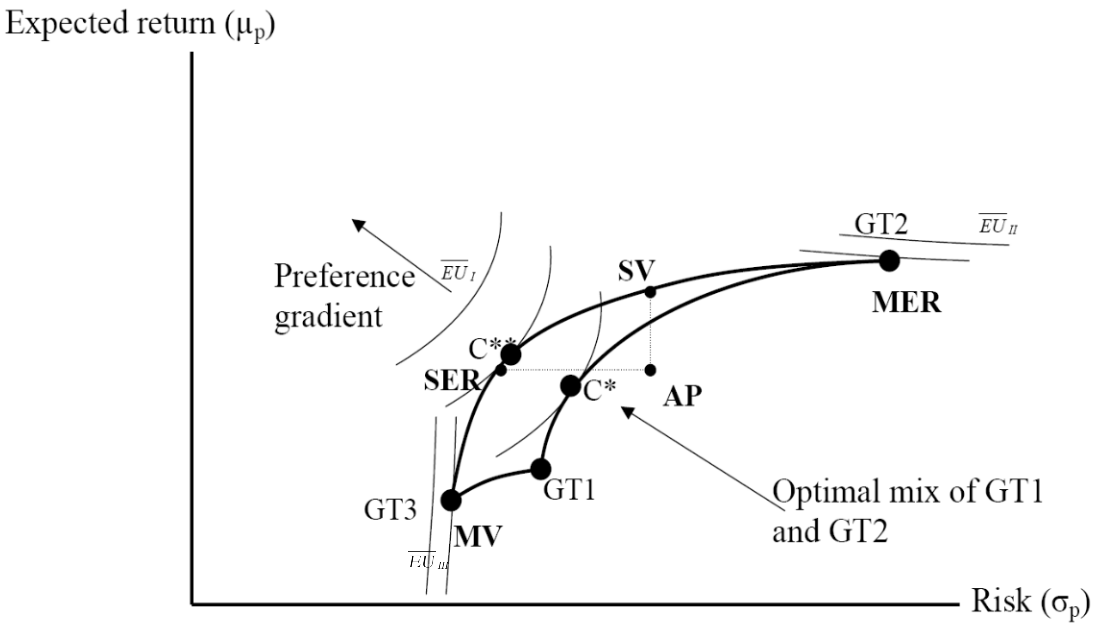
In order to determine the optimal portfolio (to be selected among the efficient ones), knowledge of the consumer's preferences would be necessary. Along an indifference curve $\overline{EU}$, expected utility is held constant. The preference gradient of Figure 1 indicates a risk-averse decision-maker who likes a higher expected return but dislikes volatility. Evidently, the optimum allocation is given by the highest-valued indifference curve that is still an element of the efficient frontier. For the frontier composed of GT1 and GT2 only, this optimum is depicted by point C*.

[4] Awerbuch (2006b) claims portfolio effects to become pronounced when correlation coefficients are below about 0.6.

[5] Awerbuch (2006b) also refers to Brealey and Myers (1994), who show that by adding riskless government bonds yielding as little as 3 percent to a stock portfolio with a rate of return of 8 percent still serves to raise the expected return at any level of risk.

If GT3 is indeed available, C** becomes the new optimum, with both higher expected return and less volatility. Clearly, C** dominates C*, demonstrating the future contribution to welfare that can be expected from the availability of additional energy technologies thanks to improved diversification.

**Figure 1:** Efficient portfolios of generation technologies (GT)




In the absence of information about utilities' and societies' degree of risk aversion, some solutions that do not depend on this information are of interest. First, a very risk-averse decision maker (presented by indifference curves $\overline{EU}_{III}$ is predicted to prefer the minimum variance (MV) portfolio, which coincides with GT3 in Figure 1. Another solution of importance is the same expected return (SER) portfolio. It contains generation technology mixes that are reshuffled as to have the same expected return as the actual portfolio (AP)[6] while being on the efficient frontier. A SER thus offers a much lower volatility than the current portfolio. Third, the same variance portfolio (SV) contains the mix of technologies that is as risky as AP but being located on the efficient frontier generates more expected return. Fourth, an almost risk-neutral decision maker (represented by indifference curves $\overline{EU}_{II}$) will opt for the maximum expected return (MER) portfolio (GT2 in the example). These four portfolios along the efficient frontier (MV, SER, SV, and MER) permit to narrow down the choice for utilities and policy makers.

Finally, the Sharpe ratio (*SR*), a measure of return-to-risk, can be used for the same purpose. It is given by

$$SR = ER_p / \sigma_p , \qquad (5)$$

[6] The actual portfolio contains the de facto power mix as of 2003 (see section 4.2).

where $E(R_p)$ is the expected return of the efficient portfolio (eq. 1) while $\sigma_p$ represents the volatility (measured as standard deviation of the expected return) of the efficient portfolio (eq. 2). A higher value of the Sharpe ratio (*SR*) is preferred over a lower one.

Some solutions (MV and MER) involve only one technology (GT3 and GT2, respectively; Figure 1). However, contrary to financial markets, where investors can allocate their entire wealth to one asset, opting for a single generation technology often is not feasible. For example, a portfolio containing photovoltaic generation only would have to be excluded unless a very long planning horizon is adopted. This consideration calls for imposing constraints, as in section 2.4 below.

## 2.3.2 Seemingly unrelated regression estimation (SURE)[7]

In view of eq. (2), portfolio risk $\sigma_p$ depends on individual standard errors $\sigma_i$ and the correlations between returns $\rho_{ij}$. As argued before, it is important to derive estimates of the covariance matrix (i.e. of $\sigma_i$ and $\sigma_{ij}$) that are reasonably time-invariant. In each time series of electricity generation costs considered, this calls for the estimation of predicted values $\hat{R}_{i,t} = R_{i,t} - \hat{u}_{i,t}$ that do not contain a systematic shift. Such values can be computed from the residuals $\hat{u}_{i,t}$ of the following autoregressive process of order *j* (sometimes complemented by a time variable)

$$R_{i,t} = \alpha_{i0} + \sum_{j=1}^{m} \alpha_{ij} \cdot R_{i,t-j} + u_{i,t}, \tag{6}$$

where $R_{i,t}$ is the (return) for technology *i* in year *t*, $\alpha_{i0}$ is a constant for technology *i*, $\alpha_{ij}$ is the coefficient of the return lagged *j* years, $R_{i,t-j}$ is the dependent variable (rate of return) lagged *j* years, and $u_{i,t}$ is the error term for technology *i* in year *t*.

If the shocks $u_{i,t}$ causing volatility in $R_{i,t}$ were uncorrelated across technologies, one could estimate the expected return for each electricity-generating technology separately to obtain residuals $\hat{u}_{i,t}$ and hence values for $\hat{R}_{i,t}$. However, as shown by previous research (Krey and Zweifel, 2006), error terms are significantly correlated across energy sources. This constitutes information that can be exploited for improving the efficiency of estimation, typically resulting in sharper estimates of the parameters $\alpha_{ij}$, of residuals $u_{i,t}$, and hence of the $\sigma_i$ and $\sigma_{ij}$ making

[7] This section is based on Krey and Zweifel (2006).

up the covariance matrix of returns. The pertinent econometric method is called Seemingly Unrelated Regression Estimation, or SURE for short. The SURE model consists of $m$ regression equations ($m$ is the number of electricity generation technologies), each of which satisfies the requirements of the standard regression model. The assumption that is specific to SURE is that the covariance matrix $E(\mathbf{uu'})$ is not diagonal, with $I$ the $m$ x $m$ identy matrix.

$$E(\mathbf{uu'}) = \begin{bmatrix} \sigma_{i,i} I & \sigma_{i,k} I \\ \sigma_{k,j} I & \sigma_{k,k} I \end{bmatrix}. \qquad (7)$$

By way of contrast, traditional OLS estimation would be appropriate if the disturbance terms of technologies $i$ and $k$ were not correlated. However, this does not hold for U.S. and Swiss power technologies (see section 2.4.3), giving rise to the covariance matrix shown in eq. (8) for the case of the United States,

$$\mathbf{\Omega} = E(\mathbf{uu'}) = \begin{bmatrix} \sigma_{OilOil} I & \sigma_{OilGas} I & \sigma_{OilNucl} I & \sigma_{OilWind} I & \sigma_{OilCoal} I \\ \sigma_{GasOil} I & \sigma_{GasGas} I & \sigma_{GasNucl} I & \sigma_{GasWind} I & \sigma_{GasCoal} I \\ \sigma_{NuclOil} I & \sigma_{NuclGas} I & \sigma_{NuclNucl} I & \sigma_{NuclWind} I & \sigma_{NuclCoal} I \\ \sigma_{WindOil} I & \sigma_{WindGas} I & \sigma_{WindNucl} I & \sigma_{WindWind} I & \sigma_{WindCoal} I \\ \sigma_{CoalOil} I & \sigma_{CoalGas} I & \sigma_{CoalNucl} I & \sigma_{CoalWind} I & \sigma_{CoalCoal} I \end{bmatrix}. \qquad (8)$$

In sum, SURE allows to simultaneously estimate the expected returns of all power generation technologies in one regression while taking into account the possible correlation of error terms across equations. This approach is novel and has to the best of the authors' knowledge not been applied in previous research concerned with portfolios of real assets.

### 2.3.3 Shannon-Wiener index

Whereas up to this point, shocks to expected returns were considered to be stochastic, measures of concentration reflect a concern about supplier strategies. The fewer technologies a power system relies upon, the fewer (as a rule) the number of suppliers, and the more the system is exposed to the (nonstochastic) effects of collusion and monopoly. One measure of concentration (or rather diversity) is entropy, also known as the Shannon-Wiener index given by

$$SW = \sum_{i=1}^{m} - p_i \ln(p_i), \qquad (9)$$

where $p_i$ ($i$=1,…; $m$) is the proportion of generation represented by the $i$th type of generation technology. A value below 1.00 indicates a system that is highly concentrated and therefore subject to the risk of collusion or monopoly, leading to interrupted supply and/or price hikes.

### 2.3.4 Herfindahl-Hirschman index

Another measure of concentration and therefore of security of supply is the Herfindahl-Hirschman index. This index is calculated according to

$$HH = \sum_{i=1}^{m} p_i^2 , \qquad (10)$$

where $p_i$ is the share of the $i$th technology, usually expressed as a percentage. Therefore, $HH$ = 10,000 in the case of a monopoly. Conversely, a value $HH$ < 1,000 is taken by antitrust authorities as indicating no concentration. In the present context, a value of $HH$ > 1,800 is interpreted as being problematic in terms of exposure to supply risk (Grubb, 2005).

Stirling (1998) prefers the Shannon-Wiener index over the Herfindahl-Hirschman index, primarily because the mathematical properties of the Shannon-Wiener index are more readily derived from first principles. Moreover the rank orderings of *SW* are not sensitive to changes in the base of logarithm. Here, both indices will be used, since *HH* is better known in the economic literature while generating results that are consistent with those of *SW* (Grubb, 2005).

## 2.4 Efficient U.S. and Swiss power generation frontiers in 2003

### 2.4.1 The data

This study uses time-series data containing annual power generation returns for several technologies, measured in kWh electric power per U.S. dollar[8]. The data covers the years 1981 to 2003 (United States) and 1985 to 2003 (Switzerland), respectively. Throughout, generation returns comprise fuel cost, cost of current operations, and capital user cost[9]. In the case of *Nuclear* power, decommissioning and disposal are also included. The data is adjusted to contain externality surcharges for environmental damage (mainly related to health and global warming).

[8] For Switzerland, the year 2000 mean value of the Swiss Franc (CHF) exchange rate was used (U.S. Federal Reserve: http://research.stlouisfed.org).

[9] As correctly pointed out by Fabien Roques (personal communication), there are different ways to measure capital user costs, yielding different generation costs. However, the utilities concerned did not provide the background data that would permit to calculate variants of capital user cost.

The data on external costs were obtained from the European Commission (2003) for the United States[10] and from Hirschberg and Jakob (1999) for Switzerland. While based on the same methods, these studies contain several externality cost scenarios, ranging from low external costs (optimistic view) to very high costs (conservative view). The conservative estimate will be used throughout. All variables are deflated by the U.S. and Swiss CPI respectively, with 2000 serving as the base year (=100).

Table 1 presents the U.S. generation returns for 1995 and 2000, for five categories, *Oil*, *Coal*, *Gas*, *Nuclear*, and *Wind* power[11]. Returns, range between 9 and 24 kWh/U.S. Dollar in 2000, with *Oil* attaining the minimum and *Wind*, the maximum.

**Table 1:** U.S. generation returns taking account of external costs, kWh/U.S. Dollar

| Year | *Oil* | *Coal* | *Gas* | *Nuclear* | *Wind* |
|---|---|---|---|---|---|
| **1995** | 8.87 | 8.74 | 16.13 | 17.34 | 18.37 |
| **2000** | 9.03 | 10.22 | 11.48 | 22.48 | 24.18 |

The Swiss data set contains *Nuclear*[12], *Run of river*[13], *Storage hydro*[14], and *Solar*[15]. Three of the four generation technologies are comparable to the United States in terms of returns, being in the 26 to 57 kWh/U.S. Dollar range in 2000 (see Table 2). By way of contrast, *Solar* was markedly more expensive in 1995 but experienced large cost decreases since, resulting in a steady increase of return.

**Table 2:** Swiss generation returns taking account of external costs, kWh/U.S. Dollar

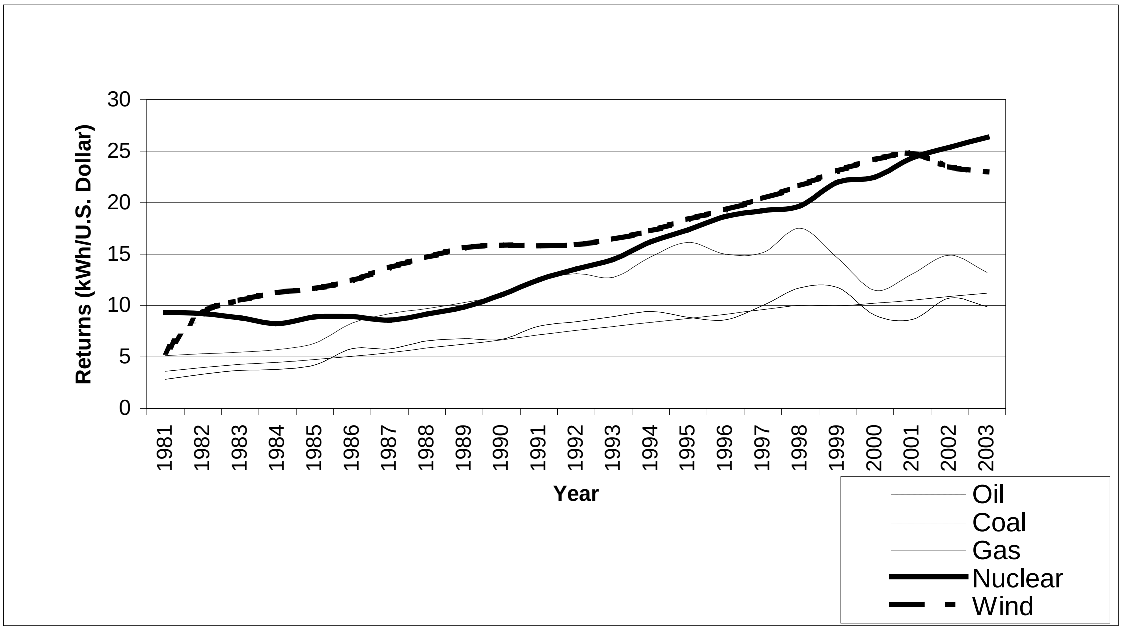
| Year | *Nuclear* | *Run of river* | *Storage hydro* | *Solar* |
|---|---|---|---|---|
| **1995** | 20.14 | 38.57 | 17.59 | 1.24 |
| **2000** | 26.65 | 57.09 | 28.80 | 1.77 |

The historical development of returns in U.S. power generation is shown in Figure 2. *Oil* exhibits large fluctuations in returns, particularly in the aftermath of 9/11. Similar fluctuations

[10] Since no external cost data for the United States were available, external cost data from the UK were used instead. The UK power industry's generation mix is similar to that of the United States.
[11] Data for *Oil*, *Coal*, *Gas*, and *Nuclear* was obtained from the UIC (2005). *Wind* [State Hawaii, USA (www.state.hi.us) and U.S. Department of Energy (www.energy.gov)]. Since the *Wind* data were not available for every year, values for 1983, 1985-1987, 1989-1994, 1996-1999 were generated by cubic spline interpolation.
[12] Data sources: KKL (2005), KKG (2005).
[13] Data source: personal correspondence.
[14] Data source: personal correspondence.
[15] RWE Schott Solar (2005); The average exchange rate of 2000 was used to convert Euro cents into U.S. cents (source: U.S. Federal Reserve). RWE Schott Solar data from Germany is used as a proxy for Swiss *Solar* power data, since *Solar* generation technologies in both countries are similar.

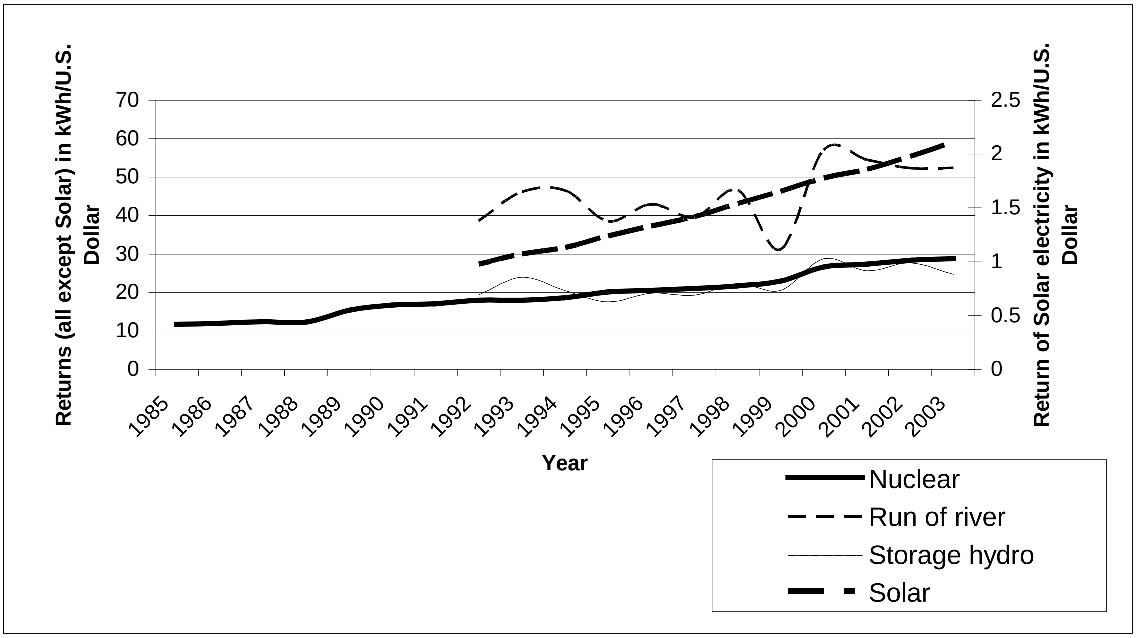
can be found for *Gas*, pointing to its strong correlation with *Oil*. By way of contrast, *Wind* and *Nuclear* might have favorable diversification properties thanks to their independence from fluctuations in fossil fuel prices.

**Figure 2:** U.S. returns in power generation (kWh/U.S. Dollar), 1981-2003




In the Swiss data set, *Run of river* exhibits the strongest fluctuations, particularly in 1999 and 2000 (see Figure 3). The likely reason is changes in financial transactions between key *Run of river* power suppliers (Axpo, 2002). In contrast, returns of *Nuclear* increase slowly over time, making it a likely candidate for diversification.

**Figure 3:** Swiss returns in power generation (kWh/U.S. Dollar), 1985/1992-2003



## 2.4.2 Actual mix of power generation as of 2003

In order to have a benchmark against which to hold efficient solutions, actual 2003 shares of current input to U.S. and Swiss power generation are displayed in Table 3. The U.S. mix contains 56 percent *Coal*, 21 percent *Nuclear*, 18 percent *Gas*, 3 percent *Oil*, and 2 percent *Wind* (Table 3a). No data was available for *hydro* power, which normally makes up for some 7 percent of total power production in the United States. Still, the ensuing analysis covers more than 90 percent of U.S. capacity, going beyond earlier studies that were limited to *Gas*, *Coal*, and *Wind* (Awerbuch, 2006b) and *Gas*, *Coal*, and *Oil*, respectively (Humphreys and McClain, 1998). The actual Swiss power mix (shown in Table 3b) consists of 40 percent *Nuclear*, 32 percent *Storage hydro*, 24 percent *Run of river*, and 4 percent *Solar*. However, *Solar* serves as a proxy for (negligible) conventional thermic and renewable sources for which data is unavailable. Again, the data account for more than 90 percent of capacity.

**Table 3a:** Actual shares of power generation technologies, United States (2003)

| United States | |
|---|---|
| Technology | Shares (in %) |
| *Coal* | 56 |
| *Nuclear* | 21 |
| *Gas* | 18 |
| *Oil* | 3 |
| *Wind* | 2 |

**Table 3b:** Actual shares of power generation technologies, Switzerland (2003)

| Switzerland | |
|---|---|
| Technology | Shares (in %) |
| *Nuclear* | 40 |
| *Storage hydro* | 32 |
| *Run of river* | 24 |
| *Solar* | 4 |

## 2.4.3 SURE results for the United States and Switzerland

Recall that SURE seeks to increase the efficiency of estimation by accounting for correlations in unobserved shocks. Table 4 provides evidence supporting this notion.

**Table 4a:** Partial correlation coefficients for U.S. returns (1981-2003)

| | *Oil* | *Coal* | *Gas* | *Nuclear* | *Wind* |
|---|---|---|---|---|---|
| *Oil* | 1 | 0.9354 | 0.9524 | 0.8303 | 0.9031 |
| *Coal* | 0.9354 | 1 | 0.8830 | 0.9588 | 0.9711 |
| *Gas* | 0.9524 | 0.8830 | 1 | 0.7503 | 0.8259 |
| *Nuclear* | 0.8303 | 0.9588 | 0.7503 | 1 | 0.9169 |
| *Wind* | 0.9031 | 0.9711 | 0.8259 | 0.9169 | 1 |

**Table 4b:** Partial correlation coefficients for $\hat{u}_{i,t}$ residuals from eq. (6), U.S. (1981-2003)

| | *Oil* | *Coal* | *Gas* | *Nuclear* | *Wind* |
|---|---|---|---|---|---|
| *Oil* | 1 | 0.0803 | 0.2704 | 0.0988 | -0.0860 |
| *Coal* | 0.0803 | 1 | 0.7754 | -0.4051 | -0.4405 |
| *Gas* | 0.2704 | 0.7754 | 1 | -0.2805 | -0.4813 |
| *Nuclear* | 0.0988 | -0.4051 | -0.2805 | 1 | -0.2265 |
| *Wind* | -0.0860 | -0.4405 | -0.4813 | -0.2265 | 1 |

In panel (a), partial correlation coefficients relating to returns (kWh/U.S. Dollar) in the United States are shown. The figures indicate strong and positive correlations. For instance, *Oil* and *Gas* exhibit a correlation coefficient of no less than 0.95. Panel (b) contains the correlations of $\hat{u}_{i,t}$, i.e. the residuals from eq. (6), which represent the components due to unobserved shocks. Correlation coefficients drop throughout, turning negative in some cases, but remain substantial. For example, the correlation across the equations for *Oil* and *Gas* is still 0.27.

The evidence for Switzerland is presented in Table 5. Here, the most marked correlation is between *Solar* and *Nuclear*, amounting to 0.98 (Panel a). The corresponding correlation between residuals $\hat{u}_{i,t}$ is estimated as 0.39 (Panel b). Correlation coefficients drop as well, but much less than in the case of the United States.

**Table 5a:** Partial correlation coefficients for Swiss returns (1992-2003)

| | *Nuclear* | *Run of river* | *Storage hydro* | *Solar* |
|---|---|---|---|---|
| *Nuclear* | 1 | 0.6421 | 0.7534 | 0.9795 |
| *Run of river* | 0.6421 | 1 | 0.8522 | 0.5535 |
| *Storage hydro* | 0.7534 | 0.8522 | 1 | 0.6879 |
| *Solar* | 0.9795 | 0.5535 | 0.6879 | 1 |

**Table 5b:** Partial correlation coefficients for $\hat{u}_{i,t}$ residuals from eq. (6), Switzerland (1992-2003)

| | *Nuclear* | *Run of river* | *Storage hydro* | *Solar* |
|---|---|---|---|---|
| *Nuclear* | 1 | 0.4934 | 0.7420 | 0.3861 |
| *Run of river* | 0.4934 | 1 | 0.7967 | 0.0205 |
| *Storage hydro* | 0.7420 | 0.7967 | 1 | -0.0021 |
| *Solar* | 0.3861 | 0.0205 | -0.0021 | 1 |

A possible explanation of this difference is that prices for primary energy sources purchased by Swiss utilities, being predominantly domestic, are much more disjoint from world market developments than their U.S. counterparts.

**Table 6:** Results of SURE regression, United States (1981-2003)

| | $\overline{R}$ | St.D. | *Const.* | $R_{t-1}$ | $R_{t-2}$ | $R_{t-3}$ | $R_{t-3}$ | *Trend* | Obs | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *Oil* | 8.23 | 2.00 | 1.84** | 1.00*** | -0.77*** | 0.73** | - | -0.69 | 19 | 0.86 |
| *Coal* | 7.83 | 2.26 | 0.88*** | 1.07*** | -0.28* | - | - | 0.07* | 19 | 0.99 |
| *Gas* | 12.58 | 2.63 | 2.99*** | 1.17*** | -1.07*** | 1.11*** | -0.67*** | 0.18 | 19 | 0.90 |
| *Nuclear* | 15.06 | 6.35 | 0.65** | 0.62*** | - | - | - | 0.44*** | 19 | 0.99 |
| *Wind* | 18.01 | 4.19 | 5.39*** | 1.15*** | -0.53 | -0.35 | - | 0.52*** | 19 | 0.99 |

*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

Table 6 displays the SURE regression results for the United States. As can be seen from the column denoted $\overline{\mathbf{R}}$, *Wind* has the largest expected return, amounting to 18.01 kWh/U.S.$, while *Coal* has the smallest expected return, at a mere 7.83 kWh/U.S.$. The standard deviations (**St.D.**) of all technologies vary widely, with *Oil* being the least volatile (2.00), and *Nuclear* the most volatile (6.35). All regressions include a time trend, which however turned out insignificant for *Oil* and *Gas*. The positive coefficients for trend in the *Coal*, *Nuclear*, and *Wind* regressions indicate that expected returns increase over time. The coefficients of determination $R^2$ are comfortably high.

**Table 7:** Results of SURE regression, Switzerland (1992-2003)

| | $\overline{\mathbf{R}}$ | **St.D.** | *Const.* | $R_{t-1}$ | $R_{t-2}$ | $R_{t-3}$ | $R_{t-4}$ | *Trend* | Obs | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *Nuclear* | 20.29 | 4.93 | 4.01** | 0.28 | - | - | - | 0.92*** | 9 | 0.94 |
| *Run of river* | 47.09 | 4.76 | 8.87 | -0.17 | 0.17 | 0.13 | - | 2.11*** | 9 | 0.45 |
| *Storage hydro* | 23.73 | 2.22 | -0.50*** | 0.04 | -0.15 | - | - | 1.85*** | 9 | 0.79 |
| *Solar* | 1.47 | 0.39 | 0.10 | 0.10 | - | - | - | 0.10*** | 9 | 0.99 |

*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

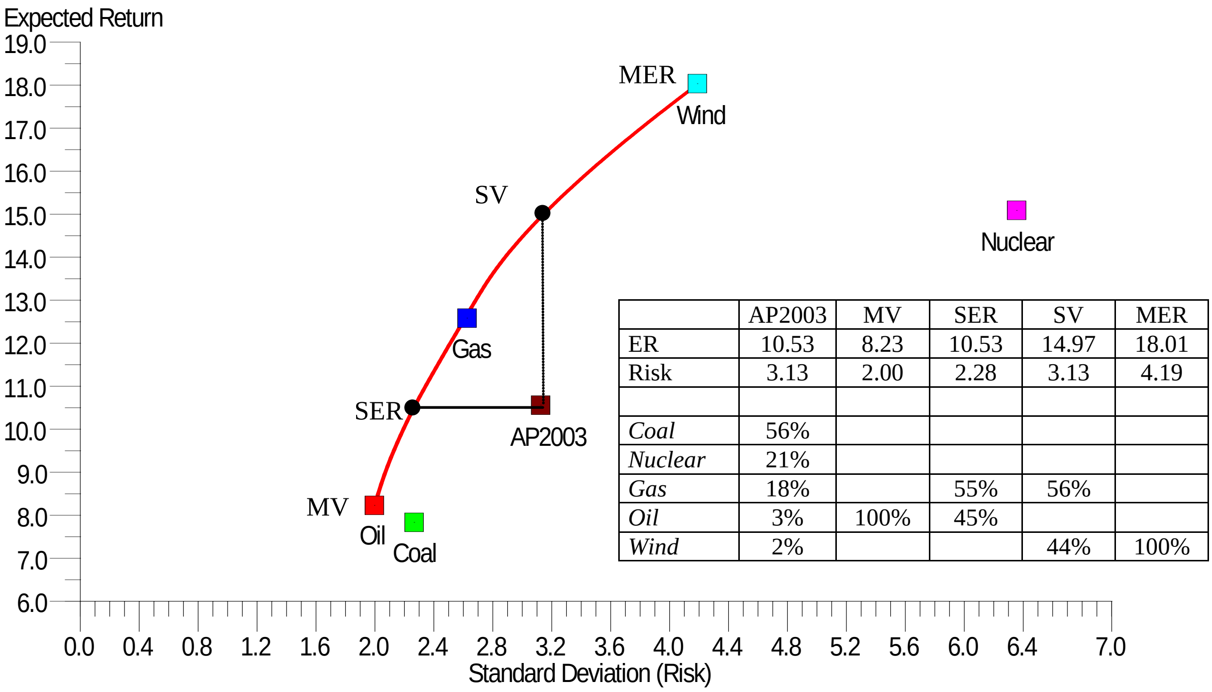
Turning to Switzerland, the $\overline{\mathbf{R}}$ column in Table 7 shows expected returns for *Run of river* to be maximum with 47.09 kWh/U.S.$, whereas *Solar* only generates 1.47 kWh/U.S.$. Comparing Tables 6 and 7, *Nuclear* in Switzerland displays both higher expected return and less risk than in the United States. The time trend has a positive and significant coefficient for all generation technologies, showing the strongest increase for *Run of river* (2.11), however only 45 percent of the variation can be explained.

## 2.4.4 Efficient power generation frontiers

### 2.4.4.1 Efficient frontiers for the United States

The efficient frontier of U.S. power generation technologies is shown in Figure 4. With no feasibility constraints applied, a U.S. utility interested in minimizing risk would opt for the MV portfolio, which contains *Oil* exclusively. There, the standard deviation (Risk) is a mere 2.00, 1.13 percentage points less than the actual portfolio (AP2003) with 3.13 (see insert). If the utility is risk-neutral, causing it to opt for the MER portfolio, then 100 percent *Wind* would be efficient, offering an expected return of 18.01, again more than the AP2003 with 10.53. Two intermediate solutions of interest are the same expected return portfolio (SER) and the same variance (SV) portfolio. For the SER, the benchmark is the 10.53 kWh/U.S.$ achieved by the AP2003, which contains 55 percent *Gas* and 45 percent *Oil*. At this mix, the SER offers the same expected return but at a lower risk (down from 3.13 to 2.28). However, it calls for more *Gas* (up from 18 to 55 percent) and more *Oil* (up from 3 to 45 percent) but no *Coal*, *Nuclear*, or *Wind*. As to the SV its expected return is 14.97 rather than 10.53 kWh/U.S.$, achieved by changing from 18 to 56 percent *Gas* and from 2 to 44 percent *Wind*. This time, *Coal*, *Nuclear* and *Oil* are not part of the efficient portfolio.

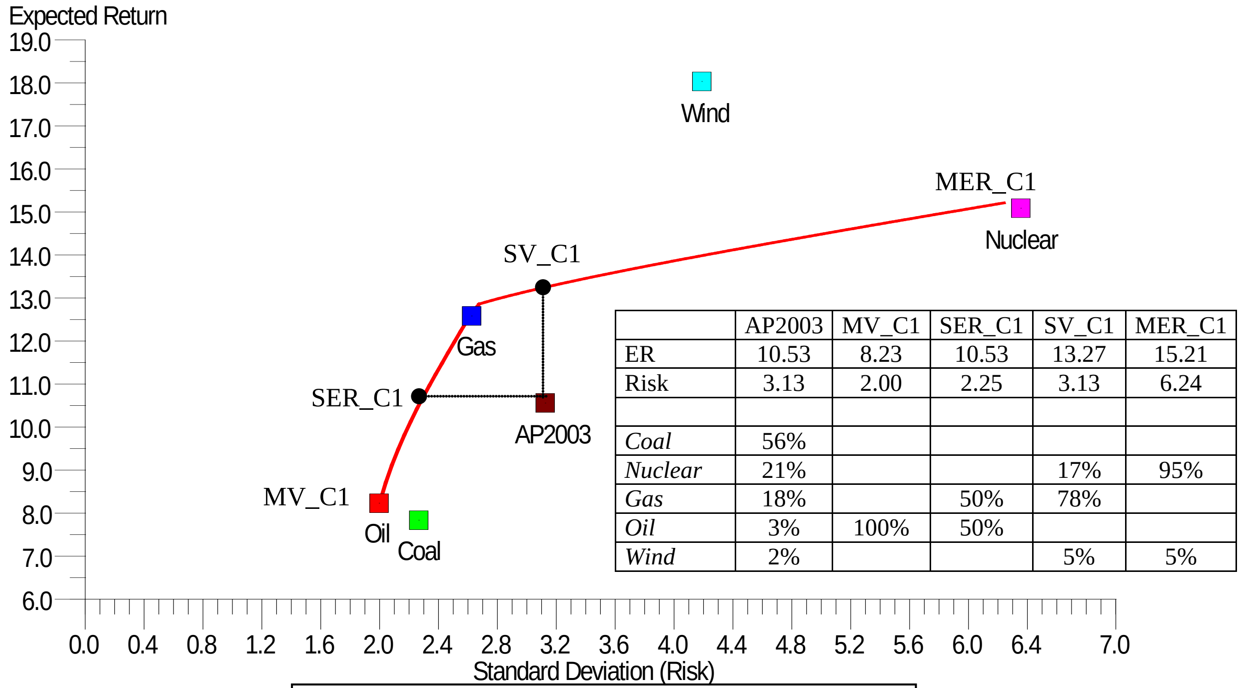
**Figure 4:** Efficient frontier for the United States
(2003, SURE-based, no constraint, high external costs)




| | AP2003 | MV | SER | SV | MER |
|---|---|---|---|---|---|
| ER | 10.53 | 8.23 | 10.53 | 14.97 | 18.01 |
| Risk | 3.13 | 2.00 | 2.28 | 3.13 | 4.19 |
| | | | | | |
| *Coal* | 56% | | | | |
| *Nuclear* | 21% | | | | |
| *Gas* | 18% | | 55% | 56% | |
| *Oil* | 3% | 100% | 45% | | |
| *Wind* | 2% | | | 44% | 100% |

However, such unconstrained portfolios are not very realistic. For instance, 44 percent *Wind* generation in 2003 would not have been technically feasible. Therefore, two additional scenarios are presented, with one constraining the share of *Wind* to a maximum of 5 percent (Figure 5, C1) and the other, constraining the shares of *Coal*, *Oil*, *Nuclear*, and *Wind* to no more than 60, 10, 25, and 5 percent, respectively (Figure 6, C2), shares that reflect technical feasibility. As expected, the MV_C1 and SER_C1 portfolios of Figure 5 contain the same mixes as in Figure 4, because *Wind* was not part of the MV and SER efficient portfolios in the first place. However, a look at the SV_C1 and MER_C1 portfolios reveals modifications. The SV_C1 portfolio places a greater weight on *Gas* (78 rather than 56 percent as in the unconstrained portfolio) and *Nuclear* (17 vs. 0 percent, compared to 21 percent in the AP2003). The constraint on *Wind* becomes binding at a share of 5 percent. Interestingly, these constraints cause only minor losses in terms of performance. For example, the SV_C1 portfolio has an expected return amounting to 13.27 as compared to 14.97 kWh/$ for the unconstrained frontier. *Nuclear* takes a weight of 95 percent in the MER_C1 portfolio, while *Wind* is constrained to its binding share of 5 percent. As expected, expected return is lower and risk higher as in the unconstrained portfolio (15.21 and 6.24 rather than 18.01 and 4.19, respectively).

**Figure 5:** Efficient frontier for the United States
(2003, SURE-based, with constraint, high external costs)



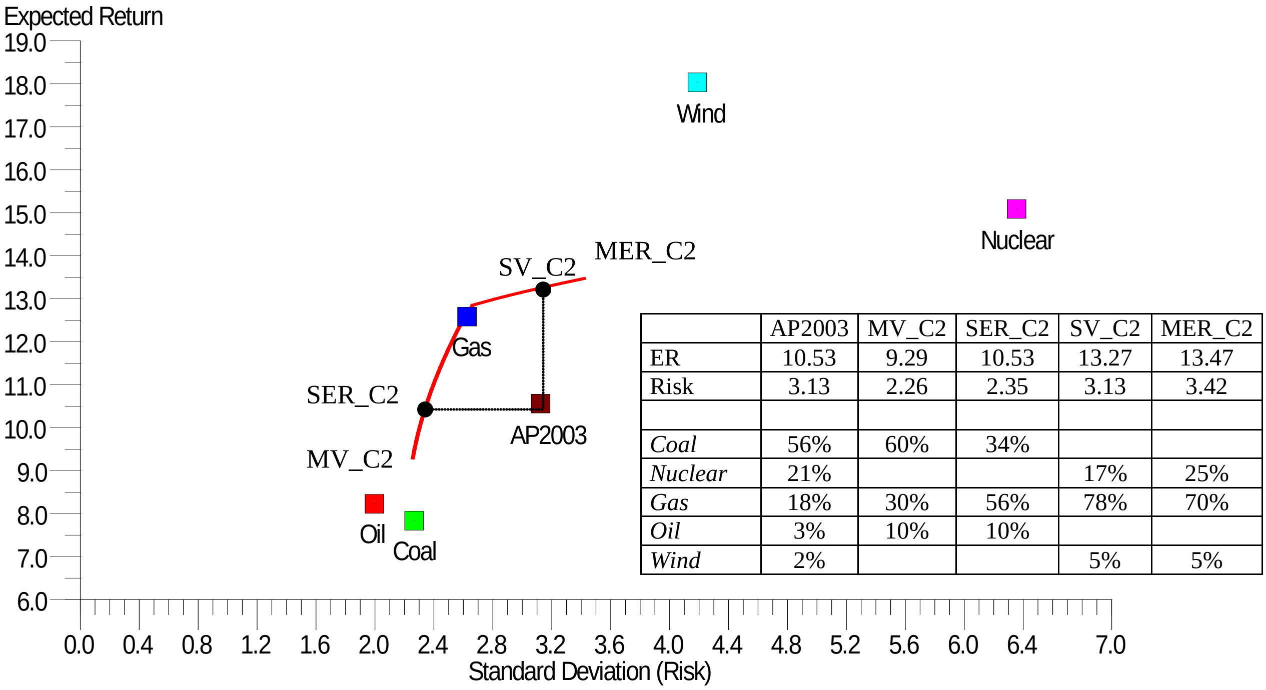

| | AP2003 | MV_C1 | SER_C1 | SV_C1 | MER_C1 |
|---|---|---|---|---|---|
| ER | 10.53 | 8.23 | 10.53 | 13.27 | 15.21 |
| Risk | 3.13 | 2.00 | 2.25 | 3.13 | 6.24 |
| | | | | | |
| *Coal* | 56% | | | | |
| *Nuclear* | 21% | | | 17% | 95% |
| *Gas* | 18% | | 50% | 78% | |
| *Oil* | 3% | 100% | 50% | | |
| *Wind* | 2% | | | 5% | 5% |

**Constraint imposed:** *Wind* ≤ 5%

By way of contrast, Figure 6 shows a more diversified mix of generation technologies, due to the imposition of item-wise maximum shares that prevent one single technology from becoming dominant. Portfolio risk increases beyond that of the minimum variance portfolios of Figures 4 and 5 but still falls short of AP2003.

Focusing on the SV portfolios, a comparison of Figure 6 with Figures 4 and 5 reveals two salient features. First, all portfolios put some weight on *Gas*, with shares ranging between 56 percent to 78 percent. This is much more than the 18 percent of AP2003. Second, maximum expected returns fall the more constraints are applied.

**Figure 6:** Efficient frontier for the United States
(2003, SURE-based, with constraints, high external costs)




| | AP2003 | MV_C2 | SER_C2 | SV_C2 | MER_C2 |
|---|---|---|---|---|---|
| ER | 10.53 | 9.29 | 10.53 | 13.27 | 13.47 |
| Risk | 3.13 | 2.26 | 2.35 | 3.13 | 3.42 |
| | | | | | |
| *Coal* | 56% | 60% | 34% | | |
| *Nuclear* | 21% | | | 17% | 25% |
| *Gas* | 18% | 30% | 56% | 78% | 70% |
| *Oil* | 3% | 10% | 10% | | |
| *Wind* | 2% | | | 5% | 5% |

**Constraints imposed:**
*Coal* ≤ 60%, *Nuclear* ≤ 25%, *Oil* ≤ 10%, *Wind* ≤ 5%

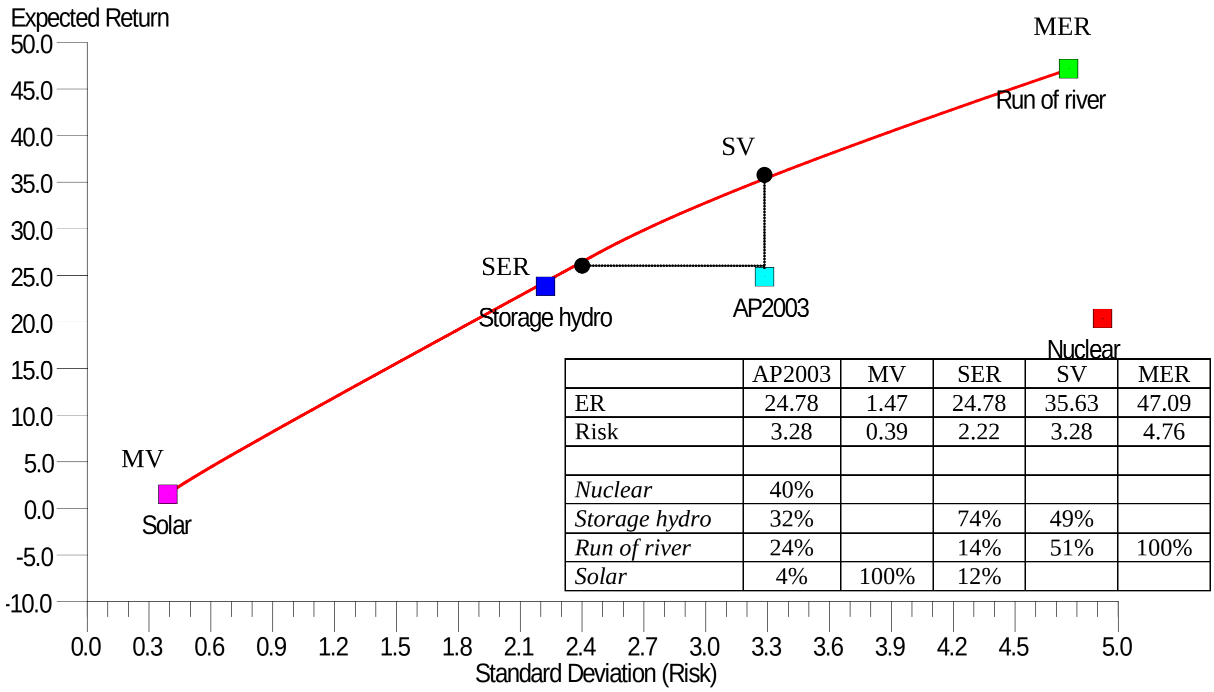
From this section, the following conclusions can be drawn with regard to the United States. A feature common to all scenarios is that a move towards the efficient frontier is possible with an increasing share of *Wind*. This feature is particularly marked in all SV portfolios, where *Wind* takes a share between 5 to 44 percent, depending on the scenario considered. In all SV portfolios, expected return exceeds that of AP2003 with no increase in risk. Assuming that utilities are rather risk-averse, the MV portfolio should be of particular interest, implying a very strong reliance on *Oil* (between 10 to 100 percent, depending on the scenario considered). The SER portfolios point to *Gas* and *Oil* with combined shares between 66 and 100 percent. If maximum returns are of interest, a combination of *Nuclear* power and *Wind* appears promising.

However, these results need to be compared with those of other studies. In his U.S. portfolio analysis, Awerbuch (2006b) finds that *Gas* generated power should play a major role in the SER, SV, and MER portfolios, with shares between 45 to 100 percent. The same holds true of *Wind* according to his MV and SER portfolios. The present study arrives at similar conclusions, with SER and SV portfolios displaying a share of *Gas* between 55 and 78 percent.

### 2.4.4.2 Efficient frontiers for Switzerland

Figure 7 displays the set of efficient power generation portfolios for Switzerland, without any constraints imposed. As in the case of the United States (Figures 4 to 6), the actual portfolio (AP2003) is located inside the efficient frontier, indicating a good deal of inefficiency (see section 2.3.1 again). The SV portfolio serves to increase expected return to 35.63 kWh/$ (up from 24.78 in the AP2003), while its volatility coincides with the actual portfolio. It implies a mix of 51 (rather than 24) percent *Run of river* and 49 (rather than 32) percent *Storage hydro*.

**Figure 7:** Efficient frontier for Switzerland
(2003, SURE-based, no constraints, high external costs)

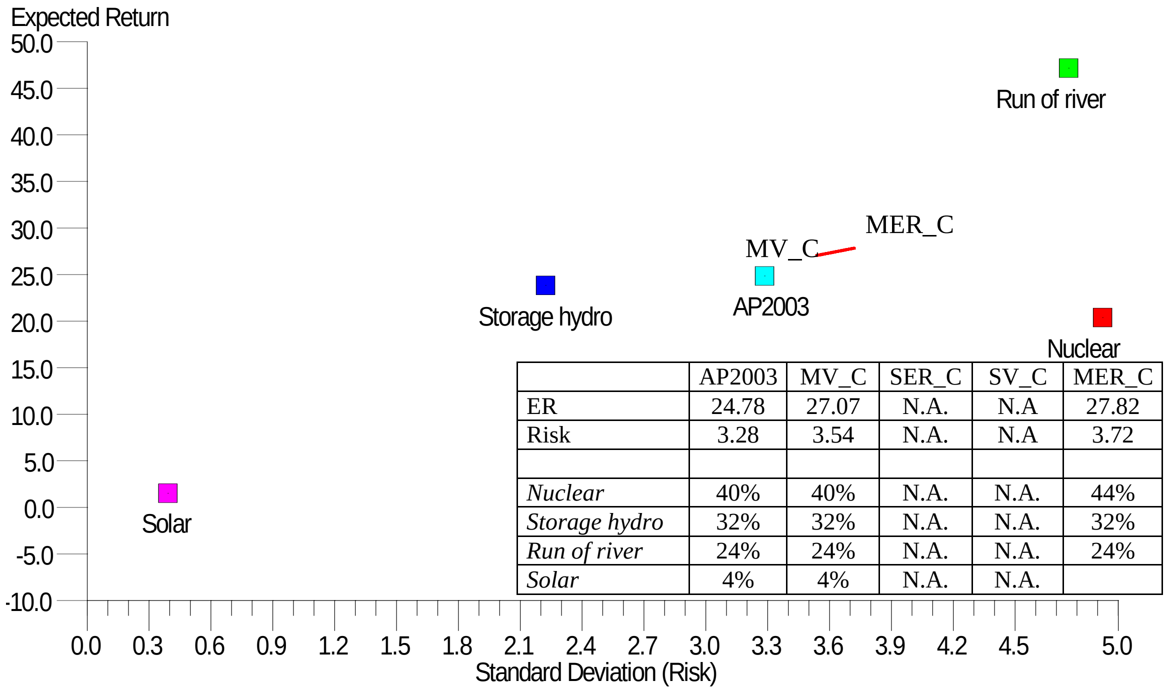



| | AP2003 | MV | SER | SV | MER |
|---|---|---|---|---|---|
| ER | 24.78 | 1.47 | 24.78 | 35.63 | 47.09 |
| Risk | 3.28 | 0.39 | 2.22 | 3.28 | 4.76 |
| | | | | | |
| *Nuclear* | 40% | | | | |
| *Storage hydro* | 32% | | 74% | 49% | |
| *Run of river* | 24% | | 14% | 51% | 100% |
| *Solar* | 4% | 100% | 12% | | |

Risk-averse utilities opting for the MV portfolio would use 100 percent *Solar*, reducing risk to 0.39, down from 3.28 in the AP2003. Conversely, the MER portfolio would imply 100 percent *Run of river*, with expected return of 47.09, twice that of AP2003. By keeping expected returns at 24.78 (the AP2003 value), utilities could reduce risk from 3.28 to 2.22, with a mix containing 74 percent *Storage hydro*, 14 percent *Run of river*, and 12 percent *Solar*.

Again, unconstrained portfolios such as these are not realistic (at least not in the short run). For shares of 100 percent *Solar* (MV) the climate is not sufficiently sunny, and for 100 percent *Run of river* (MER), the extra hydro resources are lacking (Laufer, 2004). Therefore, *Run of river*, *Storage hydro*, and *Solar* are constrained to equal their AP2003 shares, leaving only *Nuclear* to be freely determined.

**Figure 8:** Efficient frontier for Switzerland
(2003, SURE-based, with constraints, high external costs)




| | AP2003 | MV_C | SER_C | SV_C | MER_C |
|---|---|---|---|---|---|
| ER | 24.78 | 27.07 | N.A. | N.A | 27.82 |
| Risk | 3.28 | 3.54 | N.A. | N.A | 3.72 |
| | | | | | |
| *Nuclear* | 40% | 40% | N.A. | N.A. | 44% |
| *Storage hydro* | 32% | 32% | N.A. | N.A. | 32% |
| *Run of river* | 24% | 24% | N.A. | N.A. | 24% |
| *Solar* | 4% | 4% | N.A. | N.A. | |

**Constraints imposed:**
*Run of river* ≤ 24%, *Storage hydro* ≤ 32%, *Solar* ≤ 4%

The corresponding efficient frontier is shown in Figure 8. The MV_C portfolio mirrors the technology shares of the AP2003, which are 40 percent *Nuclear*, 32 percent *Storage hydro*, 24 percent *Run of river* and 4 percent *Solar*. Interestingly, it exhibits slightly more risk than the AP2003 (3.54 as compared to 3.28), which is due to the use of stabilized correlations in this particular instance (see section 2.3.2 again). At the same time, it has 2.3 percentage points more expected return (27.07 vs. 24.78), making it an attractive choice. No SER_C and SV_C portfolios can be determined, since the imposed constraints result in a solution set of measure zero. Absent risk aversion, the MER_C portfolio would be preferred, implying 44 percent *Nuclear*, 32 percent *Storage hydro*, and 24 percent *Run of river*. Not surprisingly, expected return attains a high 27.82, compared to 24.78 kWh/CHF in the AP2003, while risk increases slightly from 3.28 to 3.72.

In all, in the case of Switzerland, portfolios containing *Solar* power serve to reduce risk significantly, as can be seen in Figure 7 (MV and SER portfolios) and Figure 8 (MV_C portfolio), respectively. Conversely, *Nuclear* power helps to maximize expected return, as shown in Figure 8 (MV_C and MER_C portfolios, respectively). *Storage hydro* and *Run of river* continue to weigh heavy both in Figure 7 (SER and SV portfolios) and Figure 8 (MV_C and MER_C portfolios).

### 2.4.4.3 Comparing efficient power frontiers: a tale of two countries

Both the United States and Switzerland, different as they may be otherwise, share one salient feature with regard to power generation. Their actual portfolio AP2003 definitely falls short of the efficient frontier. On the one hand, both countries could reduce risk importantly by allocating larger shares to new-renewable technologies. As shown in Figures 4 to 6 for the United States, increasing the shares of *Wind* beyond the AP2003 value goes along with higher expected return while risk increases slightly at worst. In Switzerland, all portfolios that contain more *Solar* than AP2003 entail less risk. The SER portfolio of Figure 7 even suggests that a mix of 74 percent *Storage hydro*, 14 percent *Run of river*, and 12 percent *Solar* achieves 1.06 percentage points less risk while attaining the same expected return as AP2003.

Utilities in both countries are likely to be puzzled by these results. It seems obvious to them that increasing the shares of *Wind* (in the USA) and *Solar* (in Switzerland) must reduce expected returns. Although this notion has intuitive appeal because *Wind* and *Solar* have comparatively low returns, it does not hold true. According to eq. (1), $E(R_p)$ admittedly decreases if a below-average return component is added – provided the other shares remain (roughly) constant. However, the transition from the actual portfolio to a point on the efficient frontier causes this condition not to hold anymore. For instance, the Swiss share of *Nuclear* drops from 40 to 0 percent while that of *Solar* increases from 4 to 12 percent (see Figure 7, SER portfolio). An important implication is that in dynamic and uncertain environments, the merits of generating technologies must be determined not by evaluating single technologies, but technology portfolios. This is also the key explanation for the divergence between users' actual choices and efficient choices. In the past, utilities and policy makers have been selecting generating technologies solely on an individual, case-per-case basis, failing to consider their contribution to overall portfolio performance.

On the whole, remaining within the technically feasible and assuming that U.S. utilities are risk-averse, it appears that they would have gained by adopting the MV_C2 portfolio by 2003, containing 60 percent *Coal*, 30 percent *Gas*, and 10 percent *Oil*. This mix would have reduced volatility by 0.8 percentage points but also expected return by 1.2 points below the AP2003 benchmark. On the other hand, Swiss utilities may be said to act in an efficient manner by adopting the MV_C portfolio, which is identical to the AP2003 (made up of 40 percent *Nuclear,* 32 percent *Storage hydro*, 24 percent *Run of river*, and 4 percent *Solar*).

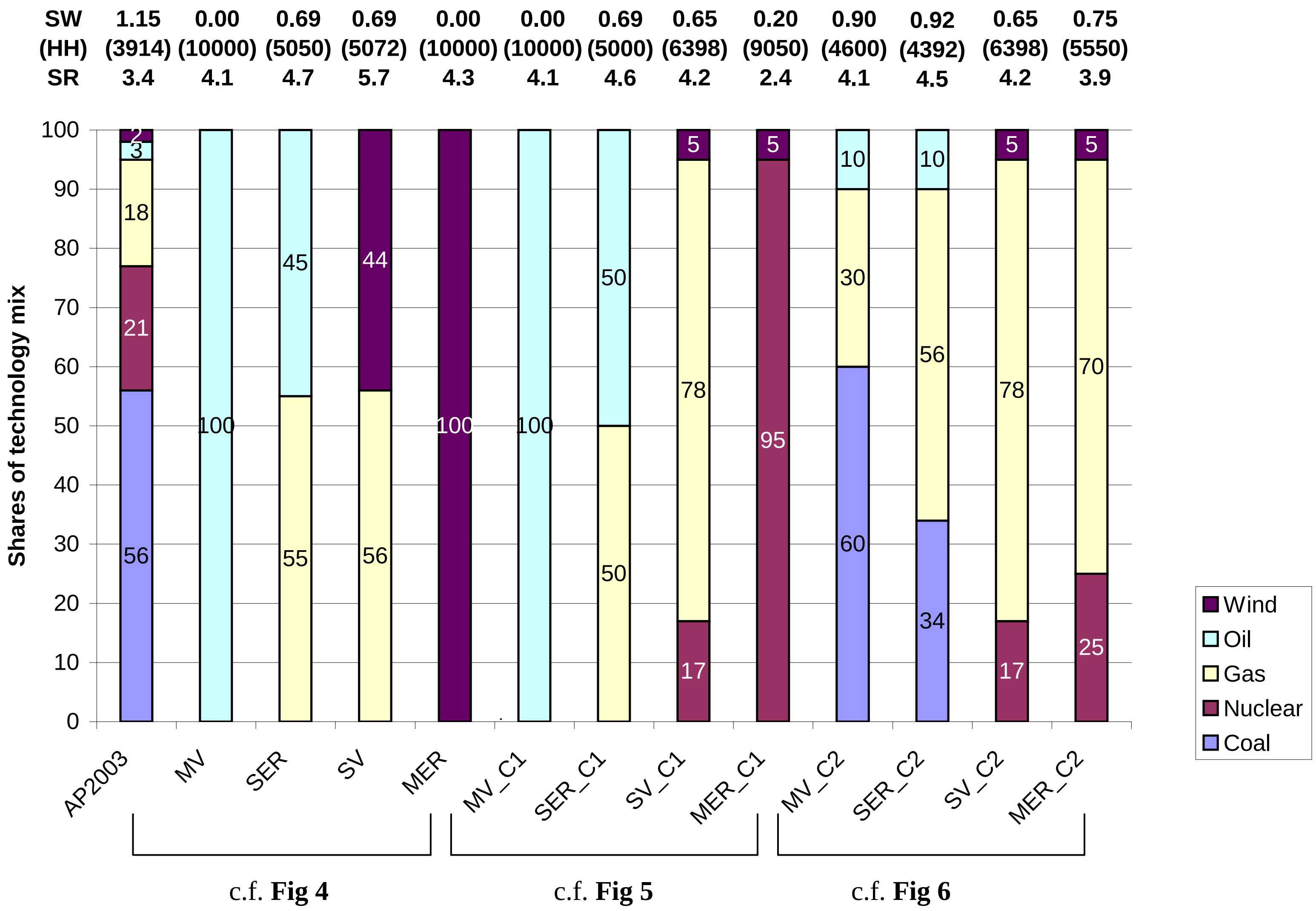
## 2.4.5 Supply security

Current concentration values for U.S. and Swiss power generation portfolios are obtained by calculating the Shannon-Wiener (*SW*) and the Herfindahl-Hirschman (*HH*) indices (see sections 2.3.3 and 2.3.4 for details). Both indices help to see whether a power generation portfolio is sufficiently diversified in terms of technologies, which also implies diversification in terms of purchases of primary energy sources. In addition, the Sharpe Ratio (*SR*) is calculated to identify portfolios with favorable return-to-risk values (see section 2.3.1).

### 2.4.5.1 Supply security for the United States

Figure 9 provides an overview of all U.S. portfolios that were presented in section 2.4.4.1, with the AP2003 appearing in the first column. Its *SW* exceeds 1.00, which corresponds to a reasonably diversified portfolio. However, the *HH* exceeds 1,800, suggesting that generation technologies and therefore purchases of primary sources for U.S. power generation are concentrated. The *SR* has a fairly low value of 3.4. With the sole exception of MER_C1 (last column, see Figure 5), all efficient portfolios offer a higher expected return than AP2003 for the same amount of risk. As expected, MV, MER, and MV_C1 portfolios are heavily concentrated and thus prone to supply disruptions. However, their Sharpe ratios are high, attaining 4.3 in the case of the MER portfolio. Incorporating short-to-medium term technological constraints, the MV_C2 and SV_C2 portfolios presumably appeal to U.S. utilities. While their Sharpe ratios are high (4.1 to 4.2), they are not well diversified according to the *SW* index. This points to a trade-off between economic efficiency and supply security in U.S. power generation.

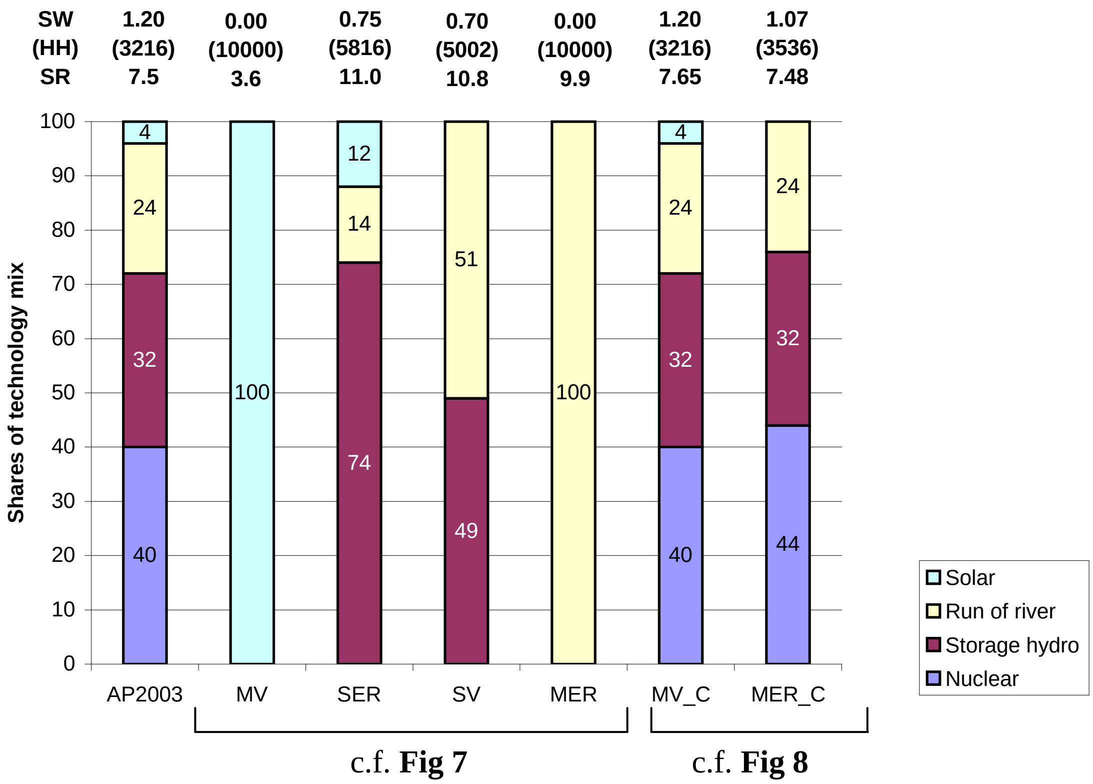
**Figure 9:** *SW*, *HH* and *SR* for the United States (2003)



### 2.4.5.2 Supply security for Switzerland

Like the actual portfolio of the United States, AP2003 of Switzerland has a *SW* in excess of 1.00, indicating a reasonably secure mix of technologies and hence primary energy sources (see Figure 10).

**Figure 10:** *SW*, *HH*, and *SR* for Switzerland (2003)




However, *HH* exceeds 1,800, implying that more diversification of generation technologies (and hence more competition between suppliers of primary energy, ceteris paribus) would be beneficial. Arguably the best technology mix for risk-averse utilities and policy makers would be the SV portfolio because it keeps portfolio volatility constant while limiting the increase of the *HH* to 5,002 and the drop of *SW* to 0.70 but raising the *SR* to a high 10.8 (compared to 3,216, 1.20, and 7.5 respectively under the AP2003). However, the implied shares of *Run of river* of 51 and *Storage hydro* of 49 percent are not attainable anytime soon. The 12 percent share of *Solar* that comes with the SER may be considered realistic. Compared to the AP2003, it serves to reduce portfolio volatility while raising *SR* to 11.0. The real difficulty lies with the concomitant increase of *Storage hydro's* share to no less than 74 percent, more than double its current value. As evidenced by Laufer et al. (2004), present *Storage hydro* technologies and geographic conditions render such a share unattainable.

In all, Swiss utilities, policy makers, and ultimately consumers face a situation that is very different from their American counterparts. If they wish to break away from a markedly inefficient AP2003 (relative to domestic potential, not compared to the United States), they have to bet on *Storage hydro* (SER). This calls for a reduction of *Run of river* capacities (which are alleged to be environmentally friendly – but recall that external costs are accounted for throughout) and scrapping *Nuclear power* entirely. On the other hand, the restricted MV_C portfolio is secure according to the *SW* while containing the same technology shares as AP2003. Risk-averse current users thus seem to be best advised to keep the AP2003 mix. By way of contrast, risk-averse utilities (and consumers) in the United States could increase their *SR* from 3.4 to almost 4.1 by opting for the SV_C2 portfolio, which, however, contains significantly more *Oil* and *Gas* and therefore would jeopardize security of supply.

## 2.5 Conclusions

The objective of this contribution was to determine the efficient frontiers of electric power generation in the United States and Switzerland, taking into account their implications in terms of security of supply. In contrast to existing portfolio studies, returns are defined as kWh of power per U.S. Dollar spent, which amounts to adopting a current user rather than an investor point of view. The observation period covers the years 1981 to 2003 (United States) and 1985 to 2003 (Switzerland), respectively. Because the error terms of the expected return regressions are correlated, seemingly unrelated regression estimation (SURE) was adopted for estimating the covariance matrix used in determining efficient portfolios.

In the absence of information about the degree of risk aversion of utilities and policy makers in the two countries, the minimum variance (MV), same expected return (SER), same variance (SV), and (as a contrast) maximum expected return (MER) portfolios were singled out for detailed analysis. One could argue that for populations as risk-averse as the U.S. and especially the Swiss, the minimum variance portfolio is the appropriate one. However, this choice may result in allocations that are too different from the actual ones to be deemed technically feasible in the short to medium run. With realistic maximum shares of 60 percent *Coal*, 25 percent *Nuclear*, 10 percent *Oil*, and 5 percent *Wind* for the United States, the following efficient portfolio of the constrained MV type (MV_C2) was obtained. It contains 60 percent *Coal*, 30 percent *Gas*, and 10 percent *Oil*, but no *Nuclear* at all. While volatility declines, both the Shannon-Wiener and the Herfindahl-Hirschman indices suggest that power generation technologies (and with them, supplies of primary energy sources) are not sufficiently diversified.

The one MV_C portfolio for Switzerland considered comprises 40 percent *Nuclear*, 32 percent *Storage hyd*ro, 24 percent *Run of river*, and 4 percent *Solar*, which mimics the AP2003. Therefore, Swiss utilities can be said to generate electricity in an efficient manner. In addition, the Shannon-Wiener index indicates a degree of diversification that is sufficient to avoid any threat to supply security.

An issue of interest would have been the efficient use of technologies along the load curve. However, this aspect had to be neglected in the present work. First, not all generating technologies can economically contribute to all load segments; for instance, hydro storage is reserved for the peak load segment for good reasons. Second, the available data does not allow a consistent assignment of cost to load segments, which seems to have been a problem with previous studies as well (Awerbuch 2006a, 2005, 2003).

To sum up, depending on the scenario considered, failure to exploit new-renewable resources such as *Wind* (in the United States) and *Solar* (in Switzerland) causes expected returns to be below and volatility to be the same or even in excess of the efficient frontier of power generating portfolios. In addition, a larger share of *Nuclear* would move both countries closer to their feasible maximum expected return (MER) portfolio. However, such a move would entail a loss in terms of supply security.

Future research should deal with several aspects that had to be neglected in this work. First, investments in energy technology often must be considered irreversible, raising the issue of their optimal timing which cannot be addressed by Markowitz theory. The appropriate approach in these cases is real options theory (Dixit and Pindyck, 1994), whose prescriptions might differ from those presented here. Second, although defining returns in terms of kilowatthours generated per U.S. Dollar has some appeal, future changes in this quantity, reflecting an investor's point of view, are relevant for planning. The present study thus needs to be complemented by using changes rather than levels of costs and productivities of energy technologies. Third, information about the risk preferences of utilities, policy makers, and ultimately citizens with regard to both the costs and prices of final energy and to purchases of primary energy inputs would be extremely valuable because this would permit to determine truly optimal (rather than a set of efficient) power portfolios. However, the present work makes first steps towards the attainment of these more ambitious goals.

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# Efficient Electricity Portfolios for the United States and Switzerland: An Investor View

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# Chapter 3

# Efficient Electricity Portfolios for the United States and Switzerland: An Investor View

## 3.1 Introduction

Like most industrial countries, the United States and Switzerland face great challenges in the provision of energy arising from increased demand by emerging economies and dwindling domestic resources. The experiences of California in 2001 (and Italy in 2003) demonstrate the high costs of power shortages to the economy. Both the United States and Switzerland are expected to confront substantial shortfalls in the provision of energy during the next twenty years. According to the U.S. National Energy Policy Development Group (NEPG), the projected gap amounts to nearly 50 percent of 2020 demand. Over the next ten years, demand for electricity in particular is predicted to increase by about 25 percent, calling for more than 200,000 MWe of new capacity (NEPG, 2001). As for Switzerland, a study conducted by the Paul Scherrer Institute estimates a power shortfall of almost 20 percent by 2020 given a (slow) demand increase of 15 percent over 2000, and more than 40 percent given a surge in demand of 30 percent (Gantner, 2000).

The solutions available to the two countries is the same, too; viz. import more power (from Canada and France, respectively); improve energy efficiency even more than expected; and increase domestic supply. However, more efficient electricity-generating portfolios could also make a contribution. Can U.S. and Swiss utilities do better as investors by modifying the current technology mix? If so, what are the attractive technologies from an investor's point of view, taking into account external costs that sooner or later will be factored into the prices of energy sources?

Financial investors take great interest in reducing their exposure to the ups and downs of the market by holding a diversified portfolio of securities. Taking into account the variances (standard deviations), covariances, and expected returns between assets, Markowitz (1952) pioneered the construction of the efficient portfolio set. An efficient portfolio does not create unnecessary risk for a given expected return, or put the other way round, it maximizes expected return for a given amount of risk, measured by the standard deviation of portfolio returns.

Indeed, the objectives of the U.S. NEPG support the portfolio approach to energy advocated here. They are "to promote dependable, affordable and environmentally sound production and distribution of energy for the future" (NEPG, 2001). The objectives of energy policy as laid down in the Swiss constitution[1] are to provide energy that should be (i) sufficient, (ii) diversified, (iii) secure, (vi) affordable, and (v) environmentally compatible. To be "dependable", energy must be available in sufficient quality, diversified, and secure; to be "affordable", its provision must be economical. Compatibility with the environment can be achieved by including external costs (which will be done in this study). Again, the portfolio approach appears to be suitable.

A comparison between the United States and Switzerland is of interest for several reasons. First, in spite of the difference in size (the U.S. population is almost 40 times larger than the Swiss), both countries heavily rely on imported fuels (gas and nuclear, respectively) for their power generation. While primary energy sources can be purchased at market prices in both countries, there are differences in their technology mix, giving rise to the question of whether they reflect differences in efficiency. Specifically, about 18 percent of total U.S. capacity for electricity was based on gas in 2003, while at present Switzerland has no gas-fueled power plants at all (see Table 1 in section 3.4.2). In the event that gas should enter its efficient electricity portfolios, Switzerland can learn from the United States. On the other hand, the United States, doing almost without hydro (7 percent of generating capacity in 2003), may benefit from learning about the performance of hydro in Switzerland (some 55 percent[2] of capacity, see panel B of Table 1). Somewhat more general insights may be expected with regard to regulation. Contrary to the United States, the Swiss electricity market continues to be highly regulated. The usual presumption would be that U.S. power generation is closer to the efficient frontier than its Swiss counterpart. The present investigation may allow to test this prediction, thus shedding light on the impact of public regulation in the case of energy. Finally, several countries (notably China and India) have to meet a rapidly increasing demand for electricity. For them, it is of considerable importance to invest in energy sources in a way that avoids inefficiency. This contribution should provide some help towards achieving that objective.

The last-mentioned consideration calls for an investor view. This means that returns are not defined in terms of kilowatthours (kWh) per Dollar spent (which would be appropriate for a

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[1] Section 6, art. 89

[2] *Run of river* and *Storage hydro* combined

current user view), but in terms of relative changes of kWh/$ over time. Accordingly, volatility is measured as the standard deviation of that quantity to determine a risk-expected return tradeoff. Indeed, investment prospects differ between the two countries. Whereas about 90 percent of all new U.S. capacity for power will be fueled by natural gas (NEPG, 2001), in Switzerland gas (much of which comes from Russia) is only slowly being considered as an alternative to nuclear power and electricity imports. Indeed, Russian state-owned Gazprom raised the specter of gauching and squeezing, a behavior that may serve as a model for suppliers of gas worldwide (Economist, 2006).

This paper is structured as follows. Section 3.2 is devoted to a review of the portfolio approach (Markowitz, 1992) as applied to the provision of energy. While Markowitz theory has been applied to the energy sources of the United States and the European Union before, a recurrent weakness is that estimated variances and covariances (the covariance matrix henceforth), which importantly determine results, may not be stable. Therefore, after specifying U.S. and Swiss efficient electricity production frontiers in section 3.3, econometric techniques for filtering out the systematic, time-invariant components of the covariance matrix are described in section 3.4.

The methodological innovation introduced in this study consists in recognizing that there are common shocks impinging on the generation costs of energy sources. Taking this correlation into account in the estimation of the covariance matrix (using so-called Seemingly Unrelated Regression Estimation, SURE) can give rise to important gains in the efficiency of estimation. To the best of the authors' knowledge, SURE has not been applied yet to the calculation of efficient electricity portfolios adopting the investor view. In section 3.5, SURE-based efficient power generation frontiers are constructed for the United States and Switzerland and contrasted with frontiers derived from Ordinary Least Squares (OLS) estimates. It will be shown that expected returns and volatilities differ greatly depending on the two estimation procedures. However, even if the SURE-based frontier is accepted as the appropriate one, there remains the open question as to which of the efficient energy mixes is optimal. While optimal choice depends on risk aversion (which is not known), the maximum expected return (MER) and the minimum variance (MV) portfolios constitute two extreme solutions that can be compared with the current portfolios of the two countries. Conclusions are offered in the final section.

## 3.2 Review of the literature

Portfolio theory and the concept of diversification have proved useful in areas other than corporate and personal investment. This review of the literature exclusively focuses on applications to energy.

Bar-Lev and Katz (1976) examine fossil fuel procurement to determine the extent to which the U.S. utility industry has been an efficient user of scarce resources. They derive a Markowitz-efficient frontier of fuel mixes which minimize the expected cost of fuels at a given risk (see section 3.3 on portfolio theory). Their results show that while generally utilities are efficiently diversified, their portfolios are characterized by both high rates of return and excessive risk, with regulation being the likely cause according to the authors. Utilities could move towards the efficient frontier by purchasing higher-priced fuels that exhibit smaller price fluctuations. However, the seminal contribution of Bar-Lev and Katz is limited in several regards. First, it comprises only fuel costs, neglecting other important components such as operating, capital user, and external costs. Fuel is assumed to constitute approximately 80 percent of total generation cost. This assumption may have been legitimate in the early 1970s when electricity was produced mainly by fuel-intensive technologies such as coal, oil, and gas. Today, nuclear, wind, and solar where fuel costs are negligible, play a more important role.

Second, their approach is best described as a current user view, since efficient current operation of a utility calls for choosing the cost-minimizing input bundle. It has been adopted by several later studies, most notably by Adegbulugbe et al. (1989), Roques et al. (2005, 2006), Doherty et al. (2005), Grubb et al. (2005), Jansen et al. (2006), and Krey and Zweifel (2009). However, utilities make a choice of technology often involving an upfront investment that promises a stream of future revenues and costs. They are thus in a position of an investor who – while not irreversibly tied to a set of assets – expects to hold a given portfolio for a few years. The appropriate view in that case is that of an investor who is concerned about changes in value over time, viz. the percentage reduction of unit cost associated with a generating technology. Indeed, this contribution is one of the first to adopt this investor view, which is actually predicated by portfolio theory, following the lead of Humphreys and McClain (1998).

A third limitation of the study by Bar-Lev and Katz is that it fails to take into account the fact that the covariance matrix of primary energy prices (and their relative changes over time) are likely to vary over time. This problem was also addressed by Humphreys and McClain, who introduced a time-varying covariance matrix in their construction of an efficient portfolio of U.S. energy sources. Estimated variances and covariances are derived from so-called Generalized Autoregressive Conditional Heteroscedastic (henceforth: GARCH) models. GARCH modeling allows to filter out systematic changes in volatility in response to shocks. Without filtering, these shocks may result in unstable estimates of the covariance matrix. The authors find that while the electric utility industry is operating close to the minimum variance (MV) portfolio, a shift towards coal would still reduce overall price volatility at a given rate of return. With the inclusion of expected external costs, the shift away from oil, while confirmed, now favors natural gas rather than coal. Humphreys and McClain also present evidence suggesting that changes in generation costs are characterized by skewness and excess kurtosis, implying that conditional densities likely are not normal. However, under these conditions GARCH does not provide useful inferences and should be replaced by an alternative approach. In addition, their study is limited to fuel price and environmental externality surcharges excluding operating and capital user costs. With a broader range of technologies considered, it becomes increasingly important to account for possible correlations between unobserved shocks impinging on the unit cost of generating technologies to achieve efficiency gains [applying Seemingly Unrelated Regression Estimation (SURE)] in estimation. The present study promises advances on these scores as well.

Yu (2003) presents a short-term market risk model again based on the Markowitz mean-variance approach, where the covariance matrix reflects differing developments of fuel prices across regional electricity markets. He includes transaction costs and other constraints such as minimum contracting quantities that limit wheeling, resulting in a mixed-integer programming problem. An interesting observation is that the resulting efficient frontier is neither smooth nor concave from below anymore, contrary to the illustration of Figure 1 in section 3.3 below.

However, Yu does not control for non-normal conditional densities, which easily lead to biased regression estimates that result in faulty predictions of future price changes. In addition, the study continues to neglect possible correlations between unobserved shocks impinging on prices. Such correlations should be of great concern in his study since it uses data from regions in the United States, which may be subject to common shocks (notably weather, as evidenced by the electricity price hikes in California that were mainly caused by dry and hot weather in the states of Washington, Utah, Nevada, and Arizona (Cicchetti et al., 2004, Ch. 18)).

Being strong advocates of the investor view, Berger et al. (2003) analyze existing and projected generating portfolios in the European Union (EU), comparing existing risk-return properties to a set of Markowitz-efficient portfolios. In general, their results indicate that both existing and projected EU technology mixes are suboptimal from a risk-return perspective. Their analysis further suggests that portfolios with lower cost increases and less risk can be attained by including greater amounts of renewables (which typically have high fixed but low variable costs, such as wind).

However, the study by Berger et al. does not take account of external costs, likely biasing results somewhat in favor of fossil fuels (but see the qualification in section 3.4.2 below). Also, their return and risk estimates are derived using financial proxies. For example, fixed and variable costs of operation and management (O&M) are approximated by using historical business data such as the S&P 500 index, the Morgan Stanley MCSI Europe index, and treasury bills. Finally, the report does not publish results of commonly known statistical tests showing whether their proxies do correlate with endogenous variables (using e.g. Shea's partial *r*-squared test, or *F*-tests for excluded instruments), and whether they are orthogonal to disturbance terms (Sargan test). There is strong support in the econometric literature of the view that weak proxies result in unreliable estimates (Greene, 2003, ch. 5). As is true of the other studies, Berger et al. fail to consider correlations of unobserved shocks impinging on generation costs.

Summing up this review, using a more comprehensive set of technologies, more comprehensive cost data, and refined econometric methodology appears to be a promising approach to obtain improved efficient frontiers for electricity-generating energy portfolios.

## 3.3 Portfolio theory

Rational holders of a portfolio of assets seek to maximize its expected return at a given level of risk or alternatively to minimize risk given a certain expected return. In the present context, the portfolio consists of generating technologies. Its expected return depends on the expected returns of the individual technologies, weighted by their share, with returns measured by the percentage change in kWh/U.S. cents of power generated. This definition is similar to that of Berger (2003) and Awerbuch and Berger (2003).

The expected return on a portfolio $E(R_p)$ consisting of *m* technologies is thus given by

$$E(R_p) = \sum_{i=1}^{m} w_i E(R_i), \text{ with } \sum_{i=1}^{m} w_i = 1, \tag{1}$$

where $E(R_i)$ is the expected return (percentage change of kWh/U.S. cents) of technology *i* and $w_i$ is the share (weight) of technology *i* in the portfolio. For example, the 2003 portfolio for the United States consists of five electricity assets, viz. *Coal*, *Nuclear*, *Gas*, *Oil*, and *Wind* (as described in section 3.4.2 below). Therefore,

$$E(R_p, US\,2003) = w_1 E(R_1) + w_2 E(R_2) + w_3 E(R_3) + w_4 E(R_4) + w_5 E(R_5). \tag{2}$$

The volatility of the portfolio's expected return involves not only the respective variances but all the covariances as well. Therefore, one has for the standard error of portfolio returns $\sigma_p$,

$$\sigma_p(US\,2003) = \sqrt{\begin{aligned} & w_1^2\sigma_1^2 + w_2^2\sigma_2^2 + w_3^2\sigma_3^2 + w_4^2\sigma_4^2 + w_5^2\sigma_5^2 + 2w_1w_2\rho_{12}\sigma_1\sigma_2 \\ & + 2w_1w_3\rho_{13}\sigma_1\sigma_3 + 2w_1w_4\rho_{14}\sigma_1\sigma_4 + 2w_1w_5\rho_{15}\sigma_1\sigma_5 + 2w_2w_3\rho_{23}\sigma_2\sigma_3 \\ & + 2w_2w_4\rho_{24}\sigma_2\sigma_4 + 2w_2w_5\rho_{25}\sigma_2\sigma_5 + 2w_3w_4\rho_{34}\sigma_3\sigma_4 + 2w_3w_5\rho_{35}\sigma_3\sigma_5 \\ & + 2w_4w_5\rho_{45}\sigma_4\sigma_5 \end{aligned}}, \tag{3}$$

where $\rho_{i,j} = \mathrm{cov}_{i,j} / (\sigma_i \sigma_j)$, $i,j = 1,...,5$, are correlation coefficients, and $\sigma_i$, the standard error of technology *i*'s returns.

The set of efficient portfolios is the solution of two equivalent problems,

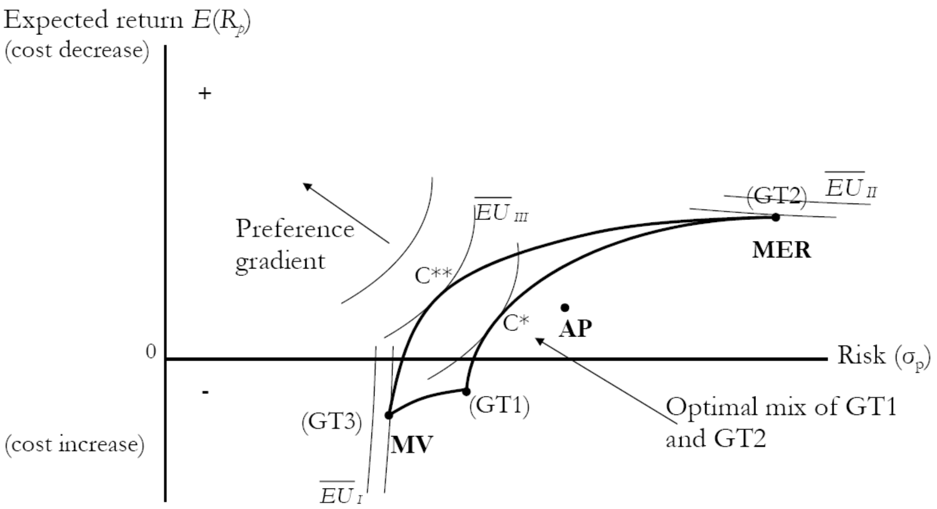
$$\max_{w_i} E(R_p) \; s.t. \sum w_i = 1, \sigma \leq \overline{\sigma}, \tag{4}$$

$$\min_{w_i} \sigma_p \; s.t. \sum w_i = 1, E(R_p) \geq \overline{R}. \tag{5}$$

The first formulation says that the expected return of the portfolio is to be maximized subject to the constraint that volatility must not exceed a limit value $\overline{\sigma}$. The second formulation says that volatility shall be minimized, without however having expected return fall below a limit value $\overline{R}$. In both cases, the decision variables are the shares $w_i$ assigned to the components of the portfolio, i.e. the generating technologies in the present context. As for Switzerland, the 2003 portfolio contains four assets, viz. *Nuclear*, *Storage hydro*, *Run of river*, and *Solar* (see section 3.4.2 for details). Equations (2) and (3) are modified accordingly.

Figure 1 illustrates the case of two generating technologies (initially; later, a third will be added). The vertical axis displays the expected return $E(R_p)$, while the horizontal axis depicts risk as measured by the standard deviation $\sigma_p$, defined in analogy to eqs. (2) and (3), respectively. For an investor, the positive segment of the vertical axis reflects the case where the costs of generation technologies are falling, causing expected returns to be positive. By assumption, let generating technology GT1 have increasing generation cost (e.g. *Run or river* in the case of Switzerland). By way of contrast, let GT2 be more risky but have positive expected returns because its cost tend to fall (e.g. *Storage hydro*). Due to the correlation terms contained in equation (3), the efficient frontier linking GT1 and GT2 (i.e. combining the two technologies) is not linear but part of an ellipse. Thus, if the correlation between two electricity generation technologies is less than perfect ($-1 < \varrho_{12} < 1$), the efficient frontier between GT1 and GT2 runs concave from below. The lower the correlation coefficient, the stronger this portfolio effect. However, the choice of the optimal among the efficient portfolios depends on the preferences of the investor. Figure 1 exhibits three types, extremely risk-averse (I), almost risk-neutral (II), and moderately risk-averse (III). Along an indifference curve, expected utility (EU) is held constant. The more the preference gradient points towards the $E(R_p)$ and away from the $\sigma_p$ axis, the more marked is the investor's risk aversion. Thus, for the intermediate type III, the solution C* is optimal. However, an actual portfolio given by point AP would be inefficient regardless of risk preferences, lying inside the efficient frontier. Note that if returns of GT1 and GT2 move in a perfectly opposite way ($\varrho_{12} = -1$), then a portfolio with no volatility at all can be constructed (Ingersoll, 1987, ch. 4). Such a portfolio always yields the same expected return, since whenever returns of GT2 are higher than expected, returns of GT1 are below expectation by an equal amount.

**Figure 1:** Efficient portfolios of generation technologies (GT)




Now let there be a third technology (GT3). This creates additional opportunities for diversification, shifting the efficient frontier upward and inward. As before, knowledge of investors risk preferences would be necessary to predict their choices of portfolio. While this knowledge is lacking with regard to U.S. and Swiss utilities, two extreme solutions are worth pointing out. As can be gleaned from Figure 1, a very risk-averse investor (type I) is predicted to opt for the minimum variance (MV) portfolio. By way of contrast, an (almost) risk-neutral utility (type II) prefers the maximum expected return (MER) portfolio, usually implying a very different mix of generating technologies (see section 3.5.2 below). Comparing these two extreme solutions permits to assess the maximum influence of risk aversion on the optimal portfolio of power generation technologies.

Note that this approach does not revolve around single technologies, but an efficient mix of several technologies. Even if a particular technology appears dominant, less promising technologies (featuring low expected returns and/or high risk) may still contribute to the portfolio because of their diversification effect [see the impact of low or even negative correlation coefficients in eq. (3)].

## 3.4 Econometric analysis

The objective of this section is to construct a correlation matrix of returns that purges the observations from singular shocks while retrieving as much information from the data as possible. To this end, observed unit cost changes will be related to a set of explanatory variables using Seemingly Unrelated Regression Estimation (SURE).

### 3.4.1 Seemingly unrelated regression estimation (SURE)

Expected rates of return pertaining to technologies [$E(R_i)$ in eq. (1)] could in principle be estimated equation by equation using Ordinary Least Squares (OLS). However, if there are unobserved common shocks impinging on technologies at the same time, the error terms $\varepsilon_{i,t}$ are correlated across equations. This constitutes information that can be used to obtain sharper estimates of the $\beta$ parameters in the following regression,

$$R_{i,t} = \beta_{i0} + \sum_{j=1}^{m} \beta_{i,j} \cdot R_{i,t-j} + \varepsilon_{i,t}, \tag{6}$$

where $R_{i,t}$ is the percentage change in generation cost (inverse of returns) of technology *i* in year *t*, $\beta_{i0}$ is a constant for technology *i* indicating a positive drift, $\beta_{i,j}$ is the coefficient pertaining to the returns lagged *k* years, $R_{i,t-j}$ is the dependent variable lagged *k* years, and $\varepsilon_{i,t}$ is the error term pertaining to technology *i* in year *t*. Where appropriate this autoregressive equation is augmented by a time trend ($Trend_{i,t}$).

While this formulation suffices to insulate expected conditional values $\hat{R}_{i,t}$ from extreme shocks (which would spill over into the estimated correlation matrix), SURE holds the promise of achieving this aim in a particular way, benefitting from the fact that the error terms are correlated across equations (see section 3.5.1.2 for empirical evidence).

In the present context, the SURE model consists of *q* regression equations (*q* being the number of electricity-generating technologies), each of which satisfies the assumptions of the standard regression model. Model (7) displays the set of equations that make up SURE of the U.S. portfolio for 2003 (coefficients are postmultiplied to prepare for the matrix notation introduced below),

$$
\begin{aligned}
R_{Coal,03} &= c_0 + R_{Coal,02}c_1 + Trend_t c_2 + \varepsilon_{Coal,03} \\
R_{Nucl,03} &= n_0 + R_{Nucl,02}n_1 + Trend_t n_2 + \varepsilon_{Nucl,03} \\
R_{Gas,03} &= g_0 + R_{Gas,02}g_1 + R_{Gas,01}g_2 + R_{Gas,00}g_3 + Trend_t g_4 + \varepsilon_{Gas,03} \\
R_{Oil,03} &= b_0 + R_{Oil,02}o_1 + R_{Oil,01}o_2 + R_{Oil,00}o_3 + R_{Oil,99}o_4 + R_{Oil,98}o_5 \\
&\quad + Trend_t o_6 + \varepsilon_{Oil,03} \\
R_{Wind,03} &= d_0 + R_{Wind,02}d_1 + Trend_t d_2 + \varepsilon_{Wind,03}.
\end{aligned} \tag{7}
$$

Generally, influences such as technological change, increases and decreases in the cost of inputs used in the production of the technology considered, and natural disasters are hypothesized to influence unit costs of electricity generation and hence returns. However, estimating such a comprehensive model is beyond the scope of this study. Rather, the relative cost change of nuclear energy in the United States in the year 2003 e.g., $R_{Nucl,03}$, is related to a constant ($n_0$), the cost change in the preceding year $R_{Nucl,02}$, and a time trend ($Trend_t$).
In analogy, the cost change of nuclear energy in Switzerland in the year 2003, $R_{Nucl,03}$, is related to a constant $(n'_0)$, the cost changes in the preceding years $R_{Nucl,02}$, $R_{Nucl,01}$, $R_{Nucl,00}$, and $R_{Nucl,99}$, and a time trend $(Trend'_t)$. The other equations relate to *Run of river* (*Ror*), *Storage hydro* (*Sh*), and *Solar* (*Solar*, which also includes other renewable energy sources such as waste),

$$
\begin{aligned}
R_{Nucl,03} &= n'_0 + R_{Nucl,02}n'_1 + R_{Nucl,01}n'_2 + R_{Nucl,00}n'_3 + R_{Nucl,99}n'_4 + Trend_t n'_5 + \varepsilon'_{Nucl,03} \\
R_{Ror,03} &= r'_0 + R_{Ror,02}r'_1 + Trend_t r'_2 + \varepsilon'_{Ror,03} \\
R_{Sh,03} &= h'_0 + R_{Sh,02}h'_1 + Trend_t h'_2 + \varepsilon'_{Sh,03} \\
R_{Solar,03} &= s'_0 + R_{Solar,02}s'_1 + R_{Solar,01}s'_2 + R_{Solar,00}s'_3 + R_{Solar,99}s'_4 + Trend_t s'_5 + \varepsilon'_{Solar,03}.
\end{aligned} \tag{8}
$$

As for $\varepsilon_{i,t}$, the $t_{th}$ element of $\varepsilon_i$, we assume that the $(\varepsilon_{1,t}, \varepsilon_{2,t}, ..., \varepsilon_{q,t})$ are iid, with $E(\varepsilon_{i,t}) = 0$ and $E(\varepsilon_{i,t}\varepsilon_{j,s}) = \sigma_{i,j}$ if $t = s$ and $= 0$ if $t \neq s$. This is the SURE specification, admitting nonzero contemporaneous correlations between error terms. Written in matrix algebra, the system (7)[3] reads,

$$
\begin{bmatrix} R_{Coal,03} \\ R_{Nucl,03} \\ R_{Gas,03} \\ R_{Oil,03} \\ R_{Wind,03} \end{bmatrix}
=
\begin{bmatrix} X_{Coal} & 0 & 0 & 0 & 0 \\ 0 & X_{Nuclear} & 0 & 0 & 0 \\ 0 & 0 & X_{Gas} & 0 & 0 \\ 0 & 0 & 0 & X_{Oil} & 0 \\ 0 & 0 & 0 & 0 & X_{Wind} \end{bmatrix}
\cdot
\begin{bmatrix} c_{Coal,03} \\ n_{Nucl,03} \\ g_{Gas,03} \\ o_{Oil,03} \\ d_{Wind,03} \end{bmatrix}
+
\begin{bmatrix} \varepsilon_{Coal,03} \\ \varepsilon_{Nucl,03} \\ \varepsilon_{Gas,03} \\ \varepsilon_{Oil,03} \\ \varepsilon_{Wind,03} \end{bmatrix}
; \tag{9}
$$

[3] The equation system for Switzerland can be constructed in the same way but for brevity is not shown.

where e.g.

$X_{Oil} = [1 \;\; R_{Oil,02} \;\; R_{Oil,01} \;\; R_{Oil,00} \;\; R_{Oil,99} \;\; R_{Oil,98} \;\; Trend_t]$ and

$O_{Oil,03} = [o_0 \; o_1 \; o_2 \; o_3 \; o_4 \; o_5 \; o_5]'$.

All other variables are defined analogously. The regressor matrix on the right-hand side is block diagonal, indicating that e.g. the cost change in the nuclear technology of 2003 is only related to its own history but not to cost changes in the other technologies. These *k* equations (involving *T* observations each) can be presented as a system by using **X** as the symbol of the block diagonal matrix in system (9),

$$\mathbf{R} = \mathbf{Xb} + \mathbf{e}, \qquad E(\mathbf{ee'}) = \mathbf{\Omega}. \tag{10}$$

The assumption that is specific to SURE is that the covariance matrix of error terms is not diagonal,

$$\mathbf{\Omega} = E(\mathbf{ee'}) = \begin{bmatrix} \sigma_{CoalCoal}I & \sigma_{CoalNucl}I & \sigma_{CoalGas}I & \sigma_{CoalOil}I & \sigma_{CoalWind}I \\ \sigma_{NuclCoal}I & \sigma_{NuclNucl}I & \sigma_{NuclGas}I & \sigma_{NuclOil}I & \sigma_{NuclWind}I \\ \sigma_{GasCoal}I & \sigma_{GasNucl}I & \sigma_{GasGas}I & \sigma_{GasOil}I & \sigma_{GasWind}I \\ \sigma_{OilCoal}I & \sigma_{OilNucl}I & \sigma_{OilGas}I & \sigma_{OilOil}I & \sigma_{OilWind}I \\ \sigma_{WindCoal}I & \sigma_{WindNucl}I & \sigma_{WindGas}I & \sigma_{WindOil}I & \sigma_{WindWind}I \end{bmatrix}. \tag{11}$$

The seemingly unrelated regression (SURE) model therefore allows to simultaneously estimate the expected returns of all power generation technologies in one regression, taking into account possible correlations of error terms across equations.

## 3.4.2 The data

The U.S. data set consists of five variables; *Coal*, *Nuclear*, *Gas*, *Oil*, and *Wind* power[4], covering the years 1982 to 2003. All variables are annual cost changes in U.S. cents per kWh electricity (inverse of expected returns), deflated by CPI, with 2000 serving as the base year (=100)[5]. The Swiss data on *Nuclear*[6] covers the years 1986 to 2003, those on *Run of river*[7] and *Storage hydro*[8] 1993 to 2003,

[4] Data for *Coal*, *Nuclear*, *Gas* and *Oil* were obtained from the UIC (2005). *Wind* (State Hawaii, USA (www.state.hi.us) and U.S. Department of Energy (www.energy.gov)). Since the *Wind* data was not available for every year, values for 1983, 1985-1987, 1989-1994, 1996-1999 were generated by cubic spline interpolation (Knott, 2000).

[5] The mean value of the exchange rate for the year 2000 was used to convert Swiss cents into U.S. cents, as published by the U.S. Federal Reserve (http://research.stlouisfed.org). Deflation is appropriate because contrary to financial investors, utilities need to adopt a long planning horizon in view of the lags involved in the construction of new plants

[6] Data sources: KKL (2005), KKG (2005)

[7] Data source: personal correspondence

and *Solar*[9], 1991 to 2003. Only aggregated data were available, marking regional variations in generating costs. However, the data do represent more than 50 percent of national production capacity in both countries. Throughout, generation costs comprise (i) fuel costs, (ii) costs of current operations, and (iii) capital user cost[10] (depreciation of book value plus interest). In the case of *Nuclear*, decommissioning and waste disposal are also included. An externality surcharge for environmental damage caused by power generation is added on top of each cost variable. These cost data are available for total production only, precluding a differentiation according to load segments, which seems to have been a problem with previous studies as well (Awerbuch 2006, 2005, 2003).

From society's point of view, the price of a product should reflect external costs to the extent that the marginal benefit of internalization effort still covers its marginal cost. This means that full internalization almost always entails an efficiency loss because in that event, expected marginal benefit necessarily is zero, while the marginal cost of internalization effort is substantial (e.g., filtering out the last 0.1 percent of toxic substances contained in a body of water causes very high cost). No external cost data for the United States were available; therefore data from the United Kingdom were used (European Commission, 2003). They serve as a good proxy because the UK generation mix and structure of the electricity industry are similar to that of the United States. Externality surcharges for Switzerland are taken from Hirschberg (1999), who implicitly assumes 100 percent internalization when dividing estimated total external cost by total final energy produced by the technology considered. Swiss and UK external cost data are comparable, both being generated by the same methods. While external costs related to health and global warming do enter calculations, no data are available for some other categories such as external costs related to agriculture and forestry. In this paper, the upper bound of social cost estimates is adopted for both countries (Hirschberg, 1999; EC, 2003).

The results of these calculations are displayed in Table 1. As noted in the Introduction section, U.S. power generation is dominated by *Coal* (panel A). However, with externality surcharges included, *Coal* cost some 9 U.S. cents (busbar) in 2003, while *Wind* power was amongst the low-cost sources. Three of the four Swiss generation technologies are comparable to those of the United States in terms of unit cost, being in the 2 to 4 U.S. cents/kWh (busbar) range in 2003 (see panel B of Table 1). By way of contrast, *Solar* was several magnitudes more expensive both in 1995 and 2003.

[8] Data source: personal correspondence

[9] RWE (2005); The average exchange rate of 2000 was used to convert Euro cents into U.S. cents (source: U.S. Federal Reserve). RWE data from Germany is used as a proxy for Swiss solar electricity data, since solar generation technologies in both countries are similar.

[10] Capital user cost can be defined in several ways. The variant "linear depreciation and interest" is used here exclusively due to lack of source data, that would permit to calculate other variants.

**Table 1: Shares in generation (percent) and cost levels (U.S. cents/kWh, prices of 2000)**

**Panel A**: United States*)

| Technology | Shares | | 1995 | 2003 |
|---|---|---|---|---|
| | 1995 | 2003 | | |
| *Coal* | 57 | 56 | 11.44 | 8.99 |
| *Nuclear* | 21 | 21 | 5.77 | 3.80 |
| *Gas* | 17 | 18 | 6.20 | 7.56 |
| *Oil* | 3 | 3 | 11.27 | 10.10 |
| *Wind* | 2 | 2 | 5.44 | 4.35 |

*) Excluding hydro (see section 3.4.3)

**Panel B**: Switzerland

| Technology | Shares | | 1995 | 2003 |
|---|---|---|---|---|
| | 1995 | 2003 | | |
| *Nuclear* | 39 | 40 | 4.97 | 3.47 |
| *Storage hydro* | 27 | 32 | 2.59 | 1.91 |
| *Run of river* | 32 | 24 | 5.69 | 4.04 |
| *Solar* | 2 | 4 | 80.76 | 47.41 |

Sources: SFOE (2004), IEA (2005)

However, note that cost levels are not relevant for investors in the capital market, who are not concerned about the price of a share. An expensive share that has the potential to still go up in the future can be part of an efficient portfolio. In full analogy, a utility, acting as an investor, would have wanted to buy into Swiss *Solar* in 1995 regardless of its initial unit cost because of the rapid decrease in the course of nine years. From an investor point of view, Swiss *Solar* should therefore figure prominently in an efficient portfolio unless it has extremely unfavorable diversification properties.

Utilities do adopt a current user view when deciding e.g. whether to buy more or less gas for fueling existing plant. However, when the choice of a technology is involved, the investor rather than the current user view is appropriate. Thus this paper seeks to answer the question, How should utilities (and policy makers) have started restructuring the electricity-generating portfolio in the 1980s (assuming they knew the cost changes occurring until 2003) in order to arrive at the MER or the MV portfolio by 2003, depending on their risk preferences?

## 3.4.3 Current U.S. and Swiss generation portfolios

To establish the respective benchmarks, the actual electricity portfolios of the United States and Switzerland (as of 2003) are presented in this section. As shown by panel A of Table 1 again, the U.S. mix predominantly consists of fossil fuels (56 percent *Coal,* 21 percent *Nuclear*, 18 percent *Gas*, and 3 percent *Oil*), with *Nuclear* accounting for another 21 percent of production. *Wind* is negligible. These shares are overestimates because no data was available for hydro power, which contributed an estimated 6 to 10 percent to total U.S. power generation between 1995 to 2003. Nevertheless, more than 90 percent of U.S. capacity is covered in this analysis, going beyond earlier work that was limited to three technologies (Awerbuch, 2006; Humphreys and McClain, 1998). The actual (2003) Swiss portfolio relies heavily on hydro (32 percent *Storage hydro*, 24 percent *Run of river*); *Nuclear* accounts for 40 percent, *Solar* (a proxy of all renewable and conventional thermic technologies), for a mere 4 percent (panel B of Table 1). Here, the data cover more than 90 percent of capacity.

# 3.5 Efficient frontiers for U.S. and Swiss power generation

## 3.5.1 Time series analysis

### 3.5.1.1 Preliminary testing

The objective is to obtain a stable estimate of the covariance matrix $\mathbf{\Omega}$ of equation (10). In order to be able to filter out the systematic (trend stable) component of $\mathbf{\Omega}$, changes in generation cost must form stationary time series. Given nonstationarity, the estimate of $\mathbf{\Omega}$ would shift over time, precluding the estimation of a reasonably stable efficient frontier [Wooldridge (2003), ch. 11].

To test for stationarity the augmented Dickey-Fuller (ADF) test was applied. Results indicate at the one percent significance level that all cost changes in the U.S. and Swiss data sets are stationary. To determine the correct lag order for the SURE regressions, several tests were applied, viz. Akaike's information criterion (AIC), Hannan & Quinn's information criterion (HQIC), Schwartz's Bayesian information criterion (SBIC), and the likelihood ratio test (LR) (Al-Subaihi, 2002; Liew, 2004). The results for the U.S. data suggest five lags for *Oil*, three lags for *Gas*, and one lag for *Coal*. One lag was used for *Wind* and *Nuclear*, based on considerations of goodness of fit in SURE (see Table 4). The results for the Swiss data suggest four lags for *Nuclear*, while in the case of *Storage hydro* and *Run of river*, one lag suffices (see appendix, Table A1). Tests are inconclusive for *Solar*.

However, Liew (2004) shows that lag selection tests may lack validity if the sample is small. Using a sample size of 25 he finds that the probability of correctly estimating the true order of an autoregressive process ranges between 58 percent (SBIC) and 60 percent (HQIC). In view of the inconclusive evidence and the fact that the coefficients on the autoregressive variables used in the SURE procedure are significant without exception, four lags were applied throughout in the case of Swiss for *Solar*.

### 3.5.1.2 Seemingly unrelated regression estimation (SURE) results

Having established the specification of the different equations, the possible presence of correlations across equations can be tested for. Panel A of Table 2 does indicate some negative correlations in the SURE residuals for the United States, with that between *Wind* and *Coal* attaining a value of -0.4246. Panel B of Table 2 tests whether OLS residuals would also have suggested SURE. While the estimated correlation coefficient for *Wind* and *Coal* would have been similar with –0.4062, correlation coefficients between *Nuclear* and *Coal* are less marked than their SURE counterparts. A striking difference can be seen in the case of *Gas* and *Wind*. The correlation in the SURE residuals is positive, while that between OLS residuals is negative.

**Table 2:** Correlation matrices for the United States

Panel A: Partial correlation coefficients for $\hat{\varepsilon}_{i,t}$ residuals from system (9), (1982-2003) using SURE

| | *Coal* | *Nuclear* | *Gas* | *Oil* | *Wind* |
|---|---|---|---|---|---|
| *Coal* | 1 | | | | |
| *Nuclear* | -0.1140 | 1 | | | |
| *Gas* | 0.7605 | 0.0113 | 1 | | |
| *Oil* | -0.3317 | 0.4461 | -0.2621 | 1 | |
| *Wind* | -0.4246 | -0.2520 | 0.1150 | -0.1492 | 1 |

Panel B: Partial correlation coefficients for $\hat{\varepsilon}_{i,t}$ residuals from equation (6), (1982-2003) using OLS

| | *Coal* | *Nuclear* | *Gas* | *Oil* | *Wind* |
|---|---|---|---|---|---|
| *Coal* | 1 | | | | |
| *Nuclear* | -0.0329 | 1 | | | |
| *Gas* | 0.7050 | -0.0004 | 1 | | |
| *Oil* | -0.2835 | 0.3670 | -0.1362 | 1 | |
| *Wind* | -0.4062 | -0.1644 | -0.2073 | 0.0998 | 1 |

**Table 3:** Correlation matrices for Switzerland

Panel A: Partial correlation coefficients for $\hat{\varepsilon}_{i,t}$ residuals from system (9), (1986-2003) using SURE

| | *Nuclear* | *Storage hydro* | *Run of river* | *Solar* |
|---|---|---|---|---|
| *Nuclear* | 1 | | | |
| *Storage hydro* | -0.4644 | 1 | | |
| *Run of river* | -0.2685 | 0.5054 | 1 | |
| *Solar* | 0.5933 | 0.0367 | -0.5907 | 1 |

Panel B: Partial correlation coefficients for $\hat{\varepsilon}_{i,t}$ residuals from equation (6), (1986-2003) using OLS

| | *Nuclear* | *Storage hydro* | *Run of river* | *Solar* |
|---|---|---|---|---|
| *Nuclear* | 1 | | | |
| *Storage hydro* | 0.3111 | 1 | | |
| *Run of river* | -0.0550 | 0.5066 | 1 | |
| *Solar* | 0.7201 | 0.2056 | -0.3824 | 1 |

In the case of Switzerland (Table 3), the highest partial correlation coefficient between SURE residuals (Panel A) is obtained for *Solar* and *Nuclear* (0.5933), followed by *Run of river* and *Storage hydro* (0.5054). In the latter case, the common unobserved shock clearly is weather conditions, in particular the amount of precipitation. The pertinent correlation coefficient between OLS residuals (Panel B) is somewhat larger with 0.7201 for *Solar* and *Nuclear* and about the same for *Run of river* and *Storage hydro* with 0.5066.

**Table 4:** Results of SURE regressions, United States (1982-2003)

| | $\overline{R}$ | *St.D.* | *Const.* | $R_{t-1}$ | $R_{t-2}$ | $R_{t-3}$ | $R_{t-4}$ | $R_{t-5}$ | *Trend* | *Obs* | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Coal* | 5.2 | 2.0 | -0.09*** | 0.02 | | | | | 0.003*** | 17 | 0.67 |
| *Nuclear* | 5.8 | 1.8 | -0.05* | 0.38** | | | | | 0.001 | 17 | 0.07 |
| *Gas* | 3.9 | 11.7 | -0.32*** | 0.10 | -0.89*** | 0.12 | | | 0.018*** | 17 | 0.67 |
| *Oil* | 2.5 | 10.4 | -1.05*** | -0.96*** | -1.35*** | -1.17*** | -1.21*** | -0.622** | 0.050*** | 17 | 0.67 |
| *Wind* | 5.4 | 6.9 | -0.03 | 0.73*** | | | | | 0.001 | 17 | 0.51 |

*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

The SURE and OLS regressions underlying these calculations are displayed in Tables 4 and 5 for the United States (for Switzerland, see appendix). The contrasts are sometimes striking. Notably, the SURE results of Table 4 (col. ***"Const.*"**) suggest a cost-increasing drift of 5 percent p.a.[11] in *Nuclear*, while according to the OLS estimate of Table 5, the hypothesis of no drift cannot be rejected. In the case of *Wind*, it is the other way round.

**Table 5:** Results of OLS regressions, United States (1982-2003)

| | $\overline{R}$ | *St.D.* | *Const.* | $R_{t-1}$ | $R_{t-2}$ | $R_{t-3}$ | $R_{t-4}$ | $R_{t-5}$ | *Trend* | *Obs* | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Coal* | 4.8 | 1.5 | -0.06*** | 0.22*** | | | | | 0.002** | 21 | 0.36 |
| *Nuclear* | 4.8 | 2.3 | -0.01 | 0.30 | | | | | -0.002 | 21 | 0.21 |
| *Gas* | 3.6 | 10.5 | -0.26** | 0.13 | -0.78*** | 0.23 | | | 0.015** | 19 | 0.69 |
| *Oil* | 2.5 | 9.7 | -0.91** | -0.85** | -1.21*** | -0.94* | -1.10** | -0.43 | 0.043** | 17 | 0.62 |
| *Wind* | 4.1 | 2.6 | -0.05** | 0.21** | | | | | 0.002 | 21 | 0.72 |

*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

In the Swiss regressions (see appendix, Tables A1 and A2), *Solar* exhibits the expected downward cost shift in the SURE estimation, which would have not been recognized as significant in the OLS alternative. On the whole, the SURE results are quite satisfactory and are preferred since they use more information than their OLS counterparts, taking into account correlations in unobserved shocks.

## 3.5.2 Construction of efficient electricity portfolios

In this section, theory and data are combined for the construction of efficient portfolios of electricity-generating technologies, or efficient electricity portfolios for short. The theory for this

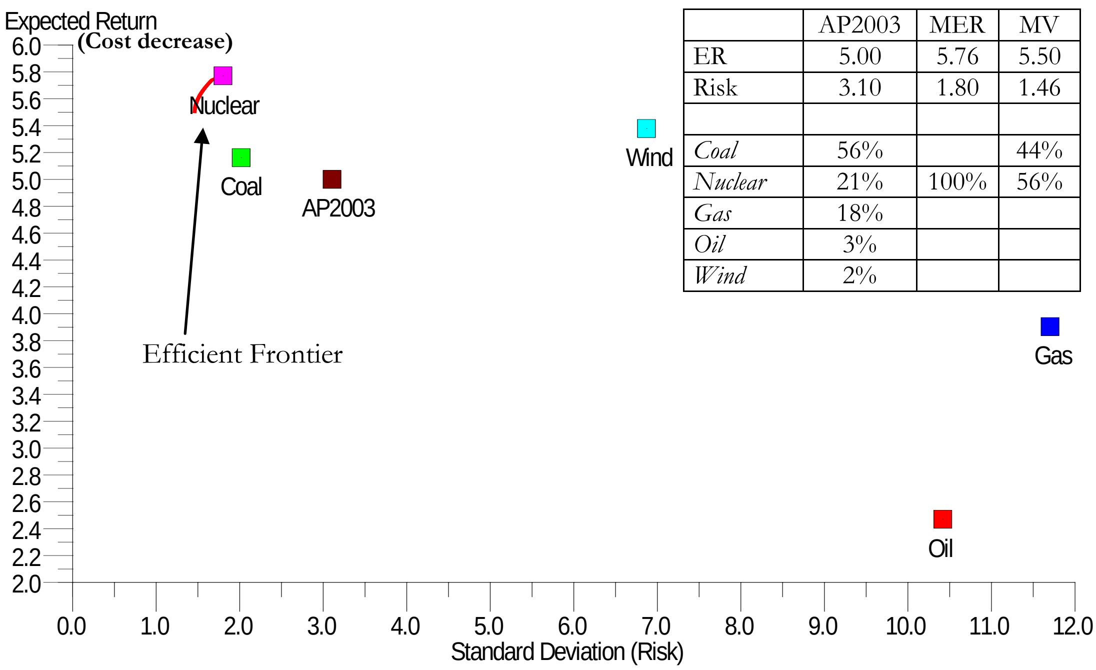
[11] A positive value indicates a cost decrease, a negative value a cost increase (see Figure 1).

is given by equations (2) and (3). It calls for an estimate of expected returns $E(R_i)$ for each technology $i$ that potentially is part of the efficient portfolio, of its standard error $\sigma_i$, and its covariances $\sigma_{ij}$. Estimates of these quantities come from the SURE results shown in Table 4 (for the United States) and Table A1 in the appendix (for Switzerland). The expected rate of return of the efficient portfolio $E(R_p)$ as well as the shares of the technologies entering that portfolio can be calculated for an arbitrary year $t$. In the following, only efficient frontiers for $t = 2003$ will be derived, defining the current efficient portfolios.

### 3.5.2.1 Current (2003) efficient electricity portfolios for the United States

Figure 2 displays the efficiency frontier for the United States without any constraints. If utilities' sole interest were to maximize expected return (thus maximizing the expected decrease of power generation costs), they would choose the MER (maximum expected return) portfolio, which contains *Nuclear* exclusively. If they wish to minimize risk, opting for the MV (minimum variance) portfolio, then a mix of 56 percent *Nuclear* and 44 percent *Coal* would be optimal.

**Figure 2:** Efficient Electricity Portfolios for the United States
(2003, SURE-based, no constraints)

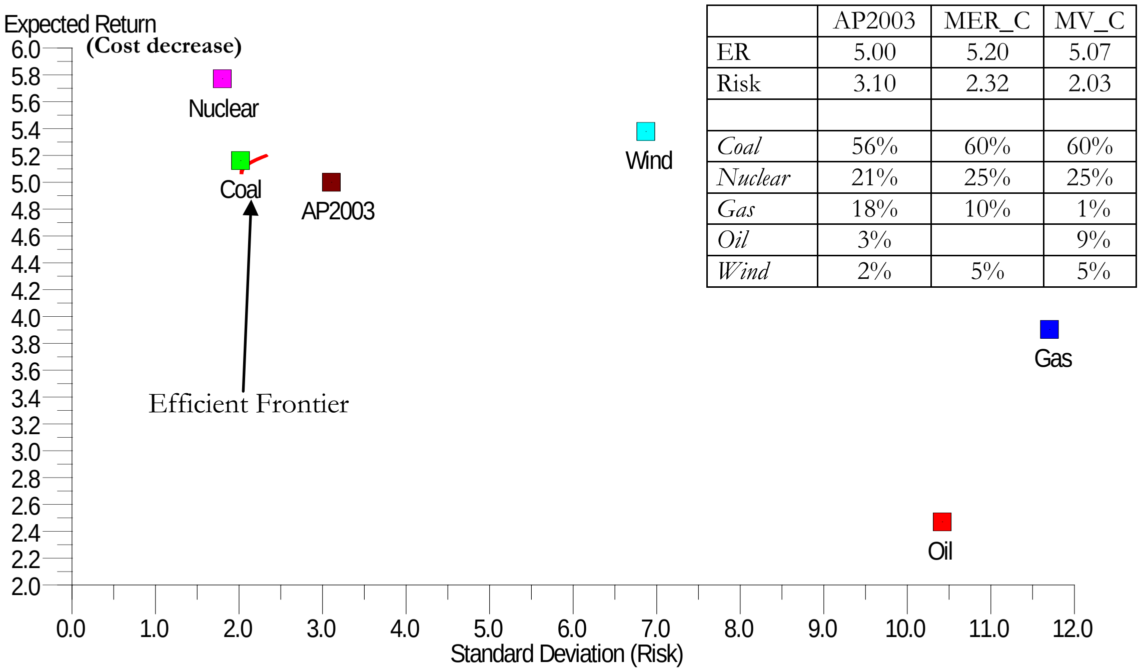



| | AP2003 | MER | MV |
|---|---|---|---|
| ER | 5.00 | 5.76 | 5.50 |
| Risk | 3.10 | 1.80 | 1.46 |
| | | | |
| *Coal* | 56% | | 44% |
| *Nuclear* | 21% | 100% | 56% |
| *Gas* | 18% | | |
| *Oil* | 3% | | |
| *Wind* | 2% | | |

Therefore, the degree of risk aversion characterizing U.S. utilities clearly matters. However, risk aversion has its price because opting for MV rather than MER would entail a cost reduction of 5.5 rather than 5.76 percent p.a. Still, the MV portfolio with its annual volatility of 1.46 percent beats the actual one whose cost reduction is 5 percent only, associated with an annual volatility of 3.10 percent.

Yet a share of *Nuclear* amounting to 100 rather than 21 percent in the MER portfolio (or 56 rather than 21 percent in the MV portfolio) must be deemed unrealistic for the United States of 2003. Therefore, Figure 3 shows an efficient frontier that takes into account that the current portfolio could be adjusted at considerable cost only. Since adjustment costs are unknown, upper limits are imposed on the individual shares for simplicity to reflect technical feasibility. For example, the share of *Wind* cannot exceed 5 percent by assumption (see insert below Figure 3).

**Figure 3:** Efficient Electricity Portfolios for the United States
(2003, SURE-based, with constraints)




| | AP2003 | MER_C | MV_C |
|---|---|---|---|
| ER | 5.00 | 5.20 | 5.07 |
| Risk | 3.10 | 2.32 | 2.03 |
| | | | |
| *Coal* | 56% | 60% | 60% |
| *Nuclear* | 21% | 25% | 25% |
| *Gas* | 18% | 10% | 1% |
| *Oil* | 3% | | 9% |
| *Wind* | 2% | 5% | 5% |

**Constraints imposed:**
*Coal* ≤ 60%, *Nuclear* ≤ 25%, *Oil* ≤ 10%, *Wind* ≤ 5%

In the MER_C (with "C" for constrained) portfolio, the generation mix now contains 60 percent *Coal*, 25 percent *Nuclear*, 10 percent *Gas*, and 5 percent *Wind*, indicating that this last constraint is binding. Compared to the actual portfolio, the cost decrease would still speed up (from 5.00 percent p.a. to 5.20 percent p.a.), while volatility would be reduced from 3.10 to 2.32 percent p.a.

In the MV_C alternative, the highest share is again allocated to *Coal* (60 percent, binding [12], up from 56 percent in the actual portfolio), followed by *Nuclear* (25 percent, binding, up from 21 percent), *Oil* (9 percent, up from 3 percent), and *Wind* (5 percent, again binding, up from 2 percent). The only technology to lose market share is *Gas* (a mere 1 percent, down from 18 percent). The rate of cost reduction would still attain 5.07 percent p.a. rather than 5.00 as in the actual portfolio, while risk declines to 2.03 from 3.10. One explanation of why *Gas* is almost phased out is its weak diversification effect, the correlation of its SURE residuals with *Coal* attaining 0.7605, the maximum value of Table 2. Therefore, current U.S. power generation is inefficient from an investor point of view. It could be made more efficient by substituting *Gas* by *Coal*, *Nuclear*, *Oil* (not in the MER_C portfolio), and *Wind*.

If correlated shocks affecting generation costs would not have been taken into account (as in past studies), the results would have been very different, quite possibly misleading investors. Figures A1 and A2 in the appendix display the OLS-based frontiers for the United States. Without constraints (Figure A1), the MER portfolio would have contained 100 percent *Coal*[13] (rather than 100 percent *Nuclear* as in the SURE-based case, see Figure 2). The MV alternative, on the other hand, would have called for a portfolio with 63 percent *Coal*, 27 percent *Nuclear*, and 10 percent *Wind*, quite different from the SURE-based solution that excludes *Wind* while allocating 56 percent (rather than 27 percent) to *Nuclear*. Moreover, investors would have little incentive to adjust their technology mix because OLS-based expected returns are at least 0.5 percentage points lower and volatilities are only slightly below the SURE-based estimates, regardless of whether or not feasibility constraints are imposed. With constraints imposed, however, OLS-based estimates would have resulted in efficient portfolios that practically coincide with the SURE-based ones (compare Figures A2 and 3). This was to be expected since most constraints are binding in both alternatives.

### 3.5.2.2 Current (2003) efficient electricity portfolios for Switzerland

Figure 4 displays the efficient electricity portfolios again (as of 2003) for Switzerland. Here, it is *Solar* rather than *Nuclear* (as in the United States) that dominates the MER portfolio with a 100 percent share. Opting for the MER portfolio, one would achieve a cost reduction of 6.67 percent p.a. (rather than the 2.00 percent p.a. cost increase with the actual portfolio), with volatility down from 10.00 to 1.05 percent p.a. The MV portfolio consists of 98 percent *Solar* and 2 percent *Nuclear*, expected return being 6.43 percent p.a. and risk, a mere 1.00. Clearly, in both countries

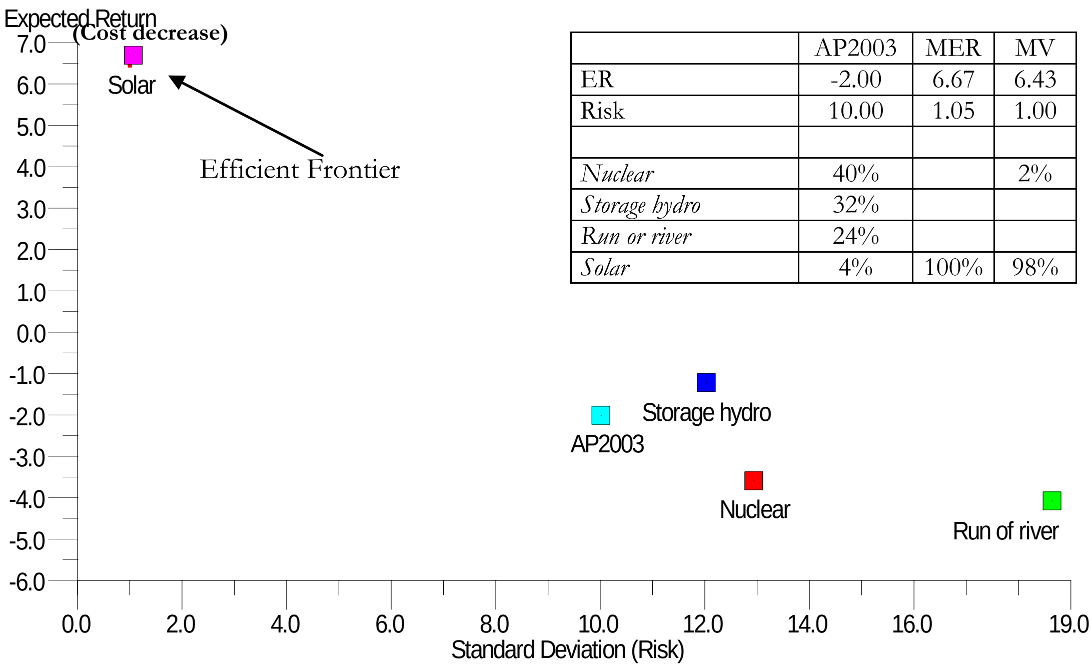
[12] Using portfolio theory for three U.S. generating technologies, Berger et al. (2003) also concluded that *Coal* dominates the MV portfolio with a share of 77 percent.

[13] Berger et. al. (2003), who do not control for correlation between unobserved shocks, also arrive at 100 percent *Coal*.

non-$CO_2$ emitting technologies (*Nuclear* in the United States and *Solar* in Switzerland) play a dominant role in the unconstrained efficient portfolios.

However, shares of *Solar* close to 100 percent must be deemed unrealistic for Switzerland. Therefore, *Storage hydro*, *Run of river*, and *Solar* are constrained to their actual shares in 2003 (32, 24 and 4 percent p.a., respectively, see insert below Figure 5), leaving only *Nuclear* unconstrained. This can be justified by noting that *Storage hydro* and *Run of river* are already being utilized to full capacity (Laufer et al., 2004), while a share of *Solar* electricity of 4 percent constitutes the limit of what could have been achieved. The corresponding efficient frontier is shown in Figure 5.

**Figure 4:** Efficient Electricity Portfolios for Switzerland
(2003, SURE-based, no constraints)



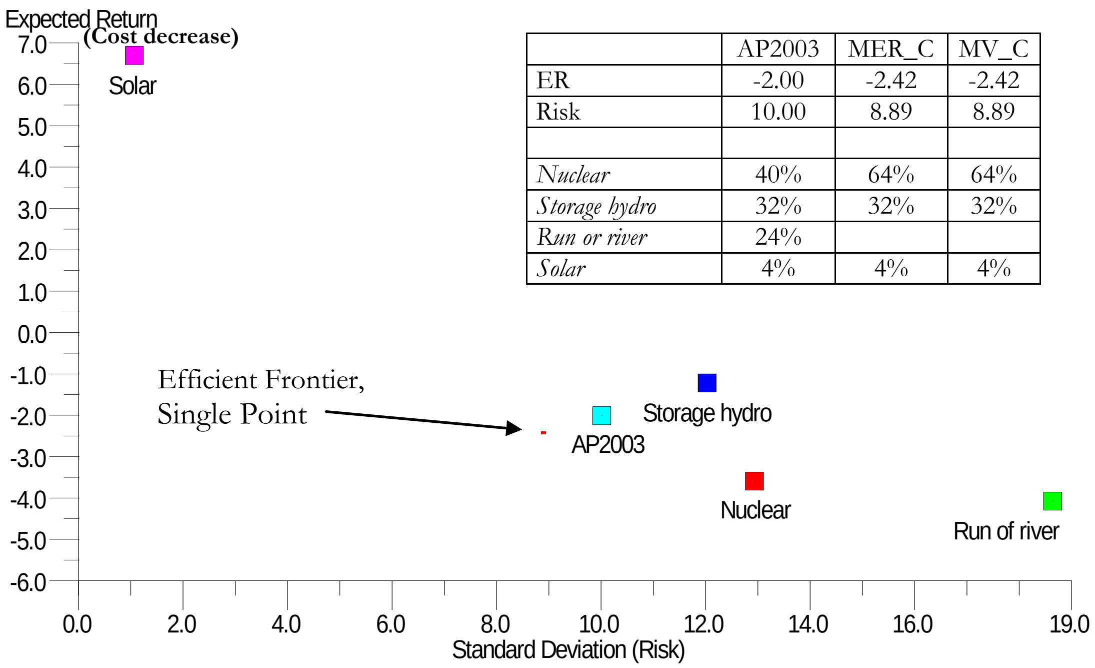

| | AP2003 | MER | MV |
|---|---|---|---|
| ER | -2.00 | 6.67 | 6.43 |
| Risk | 10.00 | 1.05 | 1.00 |
| | | | |
| *Nuclear* | 40% | | 2% |
| *Storage hydro* | 32% | | |
| *Run or river* | 24% | | |
| *Solar* | 4% | 100% | 98% |

The MER_C portfolio calls for a complete substitution of *Run of river* (actual share 24 percent) by *Nuclear* (64 percent), *Storage hydro* (32 percent, binding), and *Solar* (4 percent, binding). This surprising result is due to the fact that *Run of river* is highly correlated with *Storage hydro*, indicating that it has no diversification potential (see the correlation coefficient of 0.5054 in Table 3). At the same time, this technology has been subject to cost increases.

In all, Figure 5 suggests that if "realistic" constraints are respected, Swiss power generation could be made more efficient by allowing the share of *Nuclear* to substantially increase and abandoning *Run of river*. Generation cost would accelerate slightly, from 2.00 (actual) to 2.42 percent p.a., regardless of choice between MER and MV portfolios, but volatility would drop from 10.00 (actual) to 8.89.

Results based on OLS-estimated efficient frontiers are displayed in the appendix (Figures A3 and A4). Acting on OLS-based estimates, investors would have expected marked cost decreases rather than the cost increases implied by SURE, at the same time severely underestimating volatility. Finally, they would have wrongly slashed the share of *Storage hydro* from 32 percent to 0 percent (MER_C) or 8 percent (MV_C), respectively. Therefore, the choice of statistical specification may again well matter for decision-making by utilities.

**Figure 5:** Efficient Electricity Portfolios for Switzerland
(2003, SURE-based, with constraints)




| | AP2003 | MER_C | MV_C |
|---|---|---|---|
| ER | -2.00 | -2.42 | -2.42 |
| Risk | 10.00 | 8.89 | 8.89 |
| | | | |
| *Nuclear* | 40% | 64% | 64% |
| *Storage hydro* | 32% | 32% | 32% |
| *Run or river* | 24% | | |
| *Solar* | 4% | 4% | 4% |

**Constraints imposed:**
*Storage hydro* ≤ 32%, *Run of river* ≤ 24%, *Solar* ≤ 4%

## 3.5.2.3 United States and Switzerland compared

This section is devoted to a comparison of results obtained for the two countries as of the year 2003, using SURE-based estimates. Starting with no constraints imposed (Figures 2 and 4), the United States could have achieved an average cost reduction of 5.76 p.a. by adopting the MER portfolio, Switzerland even 6.67 percent p.a. However, both countries would have had to completely change the composition of their portfolios, to 100 percent *Nuclear* (United States) and 100 percent *Solar* (Switzerland), respectively. Turning to the MV alternative, the volatility reduction achieved amounts to 1.54 percentage points (3.10 – 1.46) for the United States, much less than for Switzerland with its 9 percentage points (10.00 – 1.00). The implications in terms of portfolio composition are quite different for the two countries as well. Whereas opting for the

MV alternative calls for 56 percent (rather than 100 percent) *Nuclear* in the case of the United States, it would leave *Solar* at almost 100 percent in the case of Switzerland.

Since shares close to 100 percent are far from reality in either country, constraints on admissible shares of technologies were imposed in Figures 3 and 5. This causes the existing amount of diversification to diminish in both countries, with *Coal* (United States) and *Nuclear* (Switzerland) becoming the principal energy sources. However, only the Swiss expected rate of return drops (from a 6.67 percent cost reduction to a 2.42 percent p.a. cost increase), associated with a marked surge in volatility.

On the whole, it appears that the U.S. electricity industry, while respecting feasibility constraints, would have gained by substituting *Gas* by *Coal*, *Nuclear*, and *Wind* technologies by 2003, regardless of the choice between the MER_C and the MV_ C portfolio. Swiss utilities would have stood to gain as well by adopting more *Nuclear* to the detriment of *Run of river*, an important source of primary energy until recently. Divergences of U.S. and Swiss investor's actual choices and efficient choices arose in past since generating technologies have been selected solely on an individual, case-per-case basis, failing to consider their contribution to overall portfolio performance.

Both industries at present fall short of their respective efficiency frontiers. In the United States, the gap amounts to a foregone 0.07 to 0.20 percentage points reduction of cost and 0.78 to 1.07 points volatility reduction (see Figure 3). In Switzerland, the estimates amount to a foregone 0.42 percentage points p.a. of cost and 1.11 points reduction of risk (see Figure 5). Therefore, there is some evidence suggesting that the more heavily regulated (Swiss) industry is characterized by a higher degree of inefficiency in the allocation of generating technologies than its largely deregulated U.S. counterpart.

## 3.6 Conclusions

The objective of this contribution was to apply portfolio theory to determine the current (2003) efficient frontiers for power generation in the United States (traditionally fossil-based) and Switzerland (traditionally hydro- and nuclear-based). The observation period covers 1982 to 2003 (United States) and 1986 to 2003 (Switzerland), respectively. Because the error terms proved to be correlated across equations, Seemingly Unrelated Regression Estimation (SURE) was adopted for estimating the covariance matrix used in determining efficient portfolios.

Interestingly, the maximum expected return (MER) portfolios of both countries boil down to one non-$CO_2$ energy source (*Nuclear* in the United States and *Solar* in Switzerland). When constraints limiting changes from the status quo are imposed to reflect the high cost associated with adjusting the technology mix, the MER_C portfolio for the United States contains 60 percent *Coal* (up from 56 percent) and for Switzerland, 64 percent *Nuclear* (up from 40 percent).

However, one could argue that for populations as risk-averse as the American and the Swiss (Szpiro, 1986), the minimum variance portfolio (MV) is appropriate. Adopting the MV criterion and imposing the same constraints, U.S. utilities would still want to assign 60 percent of their portfolio to *Coal*, almost entirely replacing *Gas*. The unit cost changes and hence returns of *Gas* are not only highly volatile but also strongly correlated with that of other technologies, depriving it of a possible diversification effect. At the same time, *Coal*-generated electricity became cleaner, causing (initially high) external costs to fall and making *Coal* very attractive from an investor point of view. In the Swiss MV_C portfolio, *Nuclear* accounts for even 64 percent while *Run of river* drops out (down from 24 percent). One is therefore led to conclude that both the current U.S. and Swiss technology mixes are inefficient even if "realistic" constraints are respected. While U.S. utilities are currently closer to their efficiency frontier than their more heavily regulated Swiss counterparts, they still may reap efficiency gains by investing more in *Coal* and moving away from *Gas*.

In contrast, efficiency frontiers estimated by OLS would tend to underestimate both expected returns and risk reduction potential in the case of the United States but overestimate achievable expected returns and underestimating risk reduction in the case of Switzerland. These discrepancies largely vanish, however, when feasibility constraints are imposed. Still, failure to account for correlation between unobserved shocks impinging on the different generation technologies using SURE does run the risk of opting for an inefficient solution. This finding contrasts with Berger et al. (2003), who concluded that the outcome of portfolio analysis is insensitive to econometric estimation techniques. However, the present study agrees with earlier ones in suggesting that utilities and policy makers, by adopting a single-technology approach, fail to take account of correlations between risky generating technologies. The consequence is a portfolio of generating technologies that is inefficient, achieving a too low expected rate of return and/or suffering from excessive volatility.

These statements are based on an investor view. To the extent that utilities are able to change their technology mix at low cost, the user view may be justified, emphasizing cost levels rather than cost changes over time. Future contributions therefore may compare the two views. They could also emphasize prediction rather than postdiction, examining whether emergent new technologies are part of future efficient frontiers. Finally, the strong assumption of a once-and-for-all decision regarding the choice of technology needs to be relaxed. A real options approach could be used to account for the irreversibility often inherent in the decision to adopt a technology. Deferring adoption may become the preferred choice in the face of stochastic cost changes caused e.g. by a liberalization of energy markets – or its failure to materialize as expected. Still, the present study provides first indications of where to go in the future in an attempt to reach the efficient mix of power-generating technologies in countries that are as diverse as e.g. the United States and Switzerland.

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# Appendix

**Table A1:** Results of SURE regressions, Switzerland (1986-2003)

| | $\overline{R}$ | *St.D.* | *Const.* | $R_{t-1}$ | $R_{t-2}$ | $R_{t-3}$ | $R_{t-4}$ | *Trend* | *Obs* | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *Nuclear* | 3.6 | 12.9 | 0.04 | -0.74*** | -0.93*** | -1.22*** | -1.37*** | -0.18*** | 9 | 0.74 |
| *Run of river* | 4.1 | 18.6 | 0.33 | -0.70*** | | | | -0.20 | 9 | 0.51 |
| *Storage hydro* | 1.2 | 12.0 | 0.25 | -0.72*** | | | | -0.02 | 9 | 0.22 |
| *Solar* | -6.7 | 1.0 | -0.34*** | -0.73*** | -0.56** | -0.61* | -0.55** | 0.01*** | 9 | 0.63 |

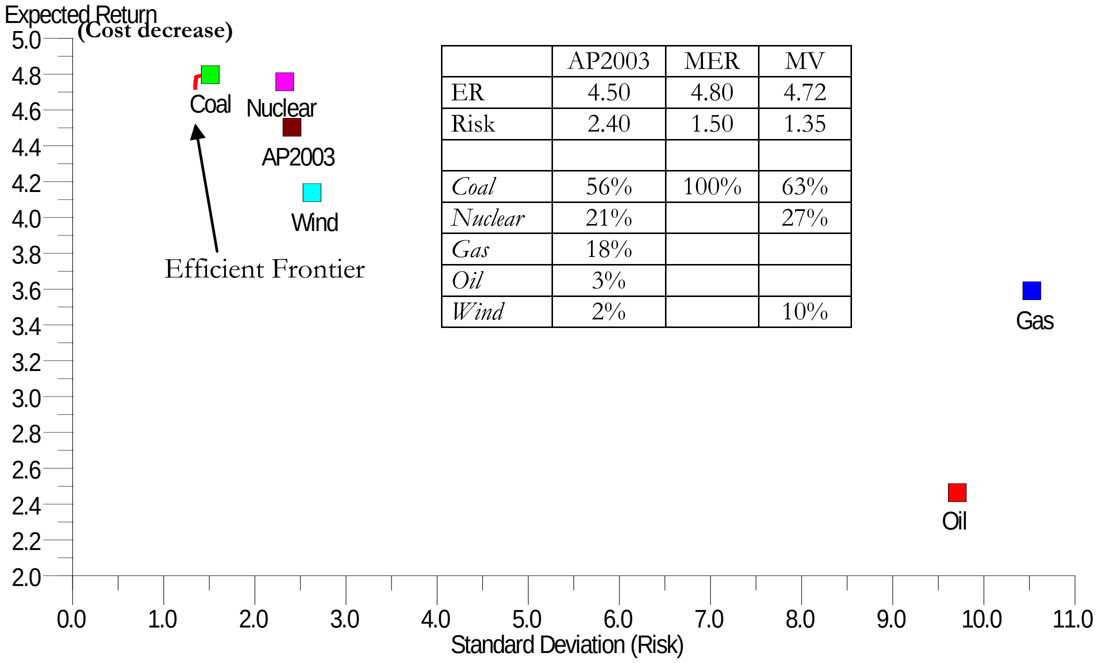
*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

**Table A2:** Results of OLS regressions, Switzerland (1986-2003)

| | $\overline{R}$ | *St.D.* | *Const.* | $R_{t-1}$ | $R_{t-2}$ | $R_{t-3}$ | $R_{t-4}$ | *Trend* | *Obs* | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *Nuclear* | -4.3 | 2.2 | -0.10* | -0.03 | -0.29 | -0.14 | -0.38* | 0.001 | 14 | 0.38 |
| *Run of river* | 1.6 | 1.6 | 0.11 | -0.64** | | | | -0.01 | 10 | 0.44 |
| *Storage hydro* | 0.8 | 9.1 | 0.20 | -0.54 | | | | -0.01 | 10 | 0.35 |
| *Solar* | -6.7 | 1.0 | -0.32 | -0.69 | -0.60 | -0.58 | -0.40 | 0.01 | 9 | 0.64 |

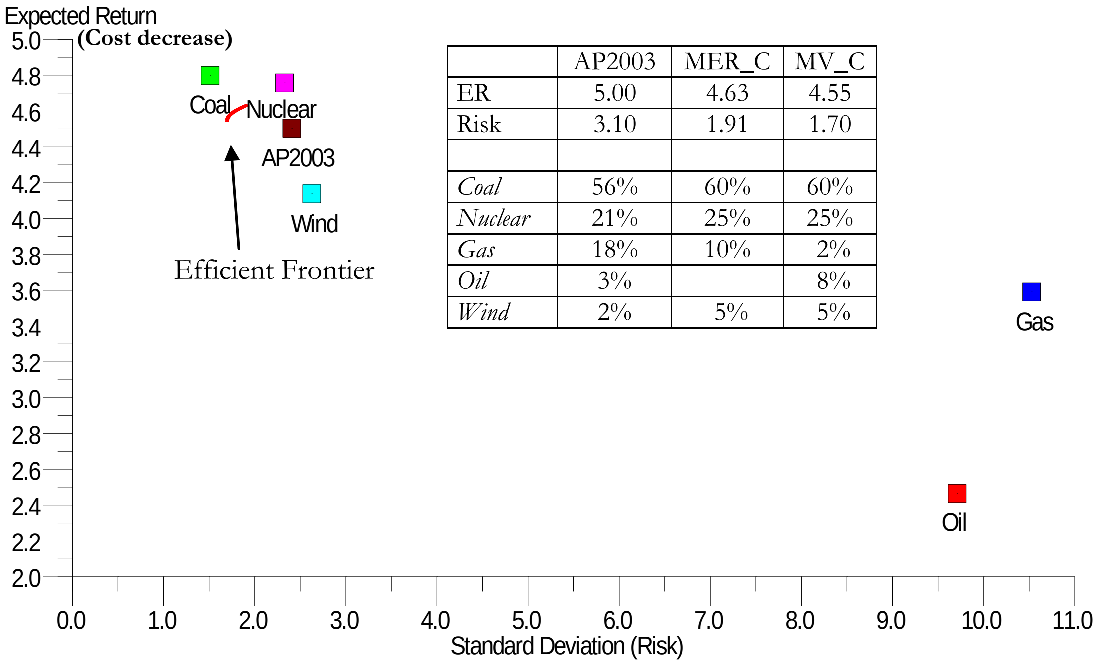
*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

**Figure A1:** Efficient Electricity Portfolios for the United States
(2003, OLS-based, no constraints)




| | AP2003 | MER | MV |
|---|---|---|---|
| ER | 4.50 | 4.80 | 4.72 |
| Risk | 2.40 | 1.50 | 1.35 |
| | | | |
| *Coal* | 56% | 100% | 63% |
| *Nuclear* | 21% | | 27% |
| *Gas* | 18% | | |
| *Oil* | 3% | | |
| *Wind* | 2% | | 10% |

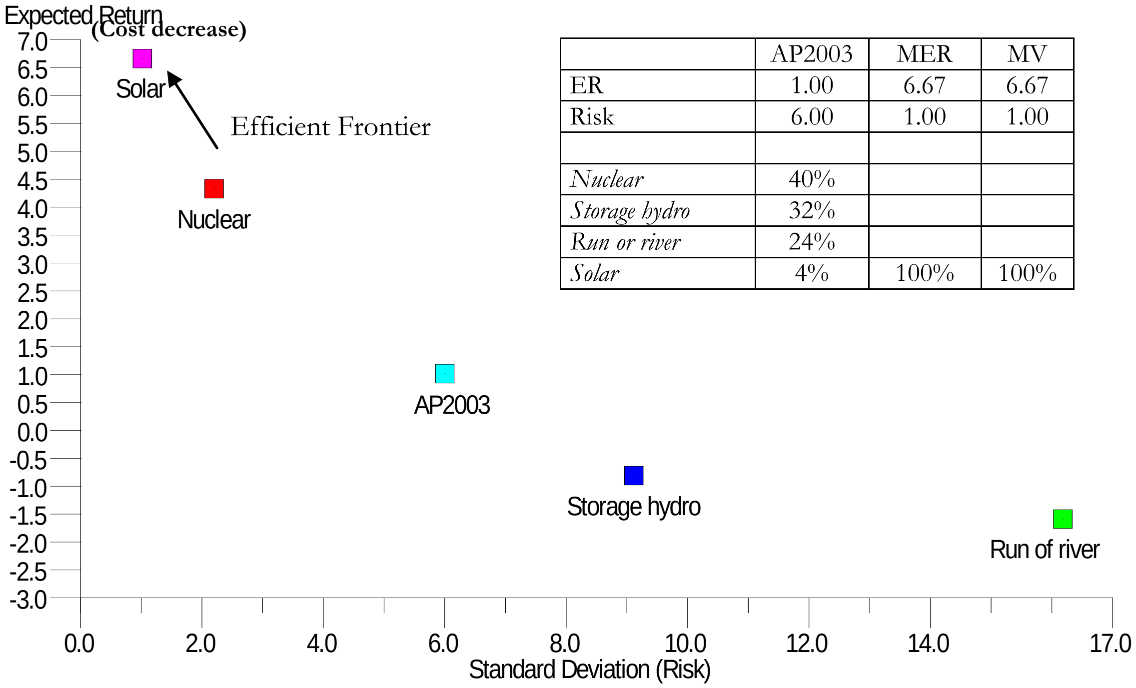
**Figure A2:** Efficient Electricity Portfolios for the United States
(2003, OLS-based, with constraints)




| | AP2003 | MER_C | MV_C |
|---|---|---|---|
| ER | 5.00 | 4.63 | 4.55 |
| Risk | 3.10 | 1.91 | 1.70 |
| | | | |
| *Coal* | 56% | 60% | 60% |
| *Nuclear* | 21% | 25% | 25% |
| *Gas* | 18% | 10% | 2% |
| *Oil* | 3% | | 8% |
| *Wind* | 2% | 5% | 5% |

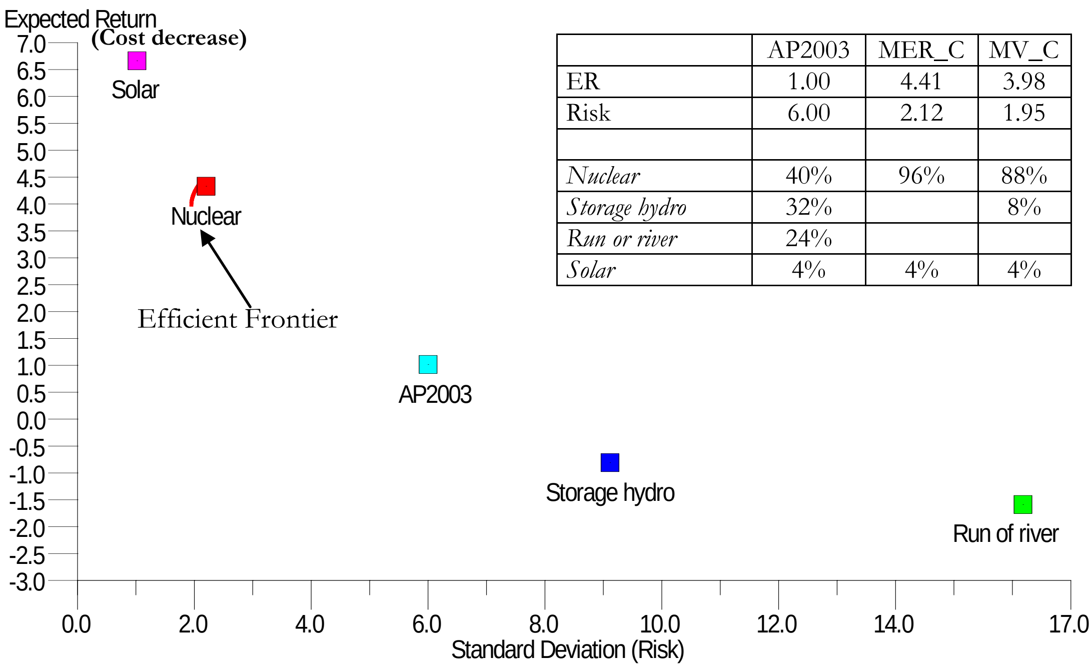
**Constraints imposed:**
*Coal* ≤ 60%, *Nuclear* ≤ 25%, *Oil* ≤ 10%, *Wind* ≤ 5%

**Figure A3:** Efficient Electricity Portfolios for Switzerland
(2003, OLS-based, no constraint)




| | AP2003 | MER | MV |
|---|---|---|---|
| ER | 1.00 | 6.67 | 6.67 |
| Risk | 6.00 | 1.00 | 1.00 |
| | | | |
| *Nuclear* | 40% | | |
| *Storage hydro* | 32% | | |
| *Run or river* | 24% | | |
| *Solar* | 4% | 100% | 100% |

**Figure A4:** Efficient Electricity Portfolios for Switzerland
(2003, OLS-based, with constraints)




| | AP2003 | MER_C | MV_C |
|---|---|---|---|
| ER | 1.00 | 4.41 | 3.98 |
| Risk | 6.00 | 2.12 | 1.95 |
| | | | |
| *Nuclear* | 40% | 96% | 88% |
| *Storage hydro* | 32% | | 8% |
| *Run or river* | 24% | | |
| *Solar* | 4% | 4% | 4% |

**Constraints imposed:**
*Storage hydro* ≤ 32%, *Run of river* ≤ 24%, *Solar* ≤ 4%

# The Impact of Liberalization on the Scope of Efficiency Improvement in Electricity-Generating Portfolios for the United States and Switzerland

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# Chapter 4

# The Impact of Liberalization on the Scope of Efficiency Improvement in Electricity-Generating Portfolios for the United States and Switzerland

## 4.1 Introduction

This study applies Markowitz mean-variance portfolio theory to calculate efficient electricity-generating frontiers for the United States and Switzerland. Along the efficient electricity frontier, the expected return of a generating portfolio is maximized for a given amount of volatility or alternatively, the portfolio risk is minimized for a given expected return. The gap between the actual portfolio (AP) and the efficient frontier indicates the scope of efficiency improvement of the generating technology portfolio. Two perspectives are considered, an investor view (where expected return is defined as (the inverse of) cost *changes*, viz. percentage change of kWh/USD) and a current user view (where expected return is (inversely) defined as kWh/USD in *levels*). A comparison of the gaps between AP and efficiency frontier may show whether U.S. deregulation paid off in terms of more expected return or less risk, or both. The main benefit of deregulation is to increase competition and choice. Before the U.S. electricity markets were liberalized more than a decade ago, consumers were forced to buy electricity from local utilities while utilities had no control over pricing. By way of contrast, Switzerland has just recently started to give large users (in excess of 100,000 kWh/year) the free choice of provider. However, electricity markets will not be fully liberalized until 2014.

Mean-variance portfolio analysis has been applied to real asset portfolios in energy, among others, by Bar-Lev and Katz (1976), Adegbulugbe et al. (1989), Humphreys and McClain (1998), Awerbuch (2000), Awerbuch and Berger (2003), Awerbuch et al. (2004), Berger et al. (2003), Yu (2003), and Krey and Zweifel (2009). Yet, to the best of the authors' knowledge, the investor and the current user view were never juxtaposed and the gaps between the APs and the efficiency never related to regulation in a cross-country comparison.

This study is structured as follows, section 4.2 provides some background information on the electricity markets of the United States and Switzerland, section 4.3 presents the methodology, while section 4.4 presents the efficiency frontiers for the United States and Switzerland. Conclusions are offered in section 4.5.

# 4.2 Background information

## 4.2.1 United States

In 2003 the United States generated approximately 4000 TWh electricity for its 290 million inhabitants by using (i) *Coal*, (ii) *Nuclear*, (iii) *Gas*, (iv) *Oil*, and (v) *Wind* technologies (due to data limitations, hydro power is not considered in this study, which contributed an estimated 9 percent to the U.S. electricity generation mix).

**Table 1:** Actual portfolio technology shares of the United States and Switzerland[1]

**Panel A**: United States

| Technology | Share in percent | |
|---|---|---|
| | 1985 | 2003 |
| | (Before liberalization) | |
| *Coal* | 64 | 56 |
| *Nuclear* | 18 | 21 |
| *Gas* | 13.5 | 18 |
| *Oil* | 4.49 | 3 |
| *Wind* | <0.01 | 2 |

**Panel B**: Switzerland

| Technology | Share in percent | |
|---|---|---|
| | 1985 | 2003 |
| | | (No liberalization) |
| *Nuclear* | 39 | 40 |
| *Storage hydro* | 34 | 32 |
| *Run of river* | 25 | 24 |
| *Solar* | 2 | 4 |

Between the 1990s and early 2000, deregulation swept through 24 states[2] affecting more than 180 million consumers. Most states did exceptionally well after deregulation, most notably Michigan, Ohio, and Texas[3], where average retail electricity prices fell below the U.S. average of 6.7 U.S. cents per kilowatt-hour[4]. Compared to 1985 (prior to deregulation), the electricity-generating

[1] Sources: SFOE (2004); IEA (2005)

[2] These are: Arizona, Arkansas, California, Connecticut, Delaware, Illinois, Maine, Maryland, Massachusetts, Michigan, Montana, Nevada, New Hampshire, New Jersey, New Mexico, New York, Ohio, Oklahoma, Oregon, Pennsylvania, Rhode Island, Texas, Virginia, and Washington D.C.

[3] California went into a crisis in 2001, when blackouts and the insolvency of PG&E, the major public utility, shocked the U.S. market. Insufficient capacity investments and bad contracting during the 1960s, 1970s and 1980s were responsible for the crisis (Borenstein/Bushnell (2000), pp. 47-48).

[4] Borenstein/Bushnell (2000), p. 47.

portfolio of 2003 shows an increase in the shares of *Nuclear*, *Gas*, and *Wind* technologies at the expense of *Coal* and *Oil* (see Table 1, Panel A).

### 4.2.2 Switzerland

Switzerland is a federal state consisting of 26 cantons, inhabited by about 7.5 million citizens. In 2003, Switzerland generated 65 TWh electricity, using (i) *Nuclear*, (ii) *Run of river*, (iii) *Storage hydro*, and (iv) *Solar* (which in this study comprises all renewables plus conventional thermic power plants and other sources). Neither industry nor households had a choice of provider. Generation, transmission, and distribution were highly regulated. Since January 2008, large users (in excess of 100,000 kWh/year) have the right to choose their electricity supplier. This is the first of many steps designed to deregulate the Swiss electricity market, which is planned to be fully liberalized by 2014, subject to a public referendum however. As can be seen in Table 1 (Panel B), the technology mix has been very stable over the last few decades, comprising between 39 to 40 percent *Nuclear* and 56 to 59 percent hydro power (*Run of river* and *Storage hydro* combined).

## 4.3 Methodology

### 4.3.1 Portfolio theory

Holders of a portfolio of assets seek to minimize risk given its expected return or alternatively maximize its expected return at a given level of risk. In the present context, the portfolio consists of electricity-generating technologies. Its expected return depends on the expected returns of the individual technologies, weighted by their shares. The risk of the portfolio depends on the covariance or correlation matrix of the individual returns.

The expected return of a portfolio $E(\mathrm{R}_p)$ consisting of $s$ risky assets is given by

$$E(\mathrm{R}_p) = \sum_{i=1}^{s} w_i E(\mathrm{R}_i), \quad \text{with } \sum_{i}^{s} w_i = 1, \tag{1}$$

where $E(R_i)$ is the expected return of technology $i$ and $w_i$ is the share (weight) of technology $i$ in the portfolio. For example, a portfolio comprising three generating technologies would have

$$E(\mathrm{R}_p) = w_1 E(\mathrm{R}_1) + w_2 E(\mathrm{R}_2) + w_3 E(\mathrm{R}_3), \tag{2}$$

with

$$\sum_{i=1}^{3} w_i = w_1 + w_2 + w_3 = 1 . \tag{3}$$

The volatility of the portfolio's expected return involves both the respective variances and covariances of the individual returns. The standard deviation ($\sigma_p$) is a common measure of risk. For a portfolio containing $s$ technologies, it is given by

$$\sigma_p = \sqrt{\sum_{i=1}^{s} w_i^2 \sigma_i^2 + 2\sum_{i \neq j} w_i w_j \rho_{ij} \sigma_i \sigma_j} \ , \tag{4}$$

where $\sigma_i$ and $\sigma_j$ are individual standard deviations of the returns of technology $i$ and technology $j$, and $\rho_{ij} = \mathrm{cov}_{ij} / (\sigma_i \sigma_j)$, $i,j = 1,...,3$, are correlation coefficients. Using the same three technology example as before, the portfolio standard deviation can be computed from

$$\sigma_p = \sqrt{w_1^2 \sigma_1^2 + w_2^2 \sigma_2^2 + w_3^2 \sigma_3^2 + 2 w_1 w_2 \rho_{12} \sigma_1 \sigma_2 + 2 w_1 w_3 \rho_{13} \sigma_1 \sigma_3 + 2 w_2 w_3 \rho_{23} \sigma_2 \sigma_3} \ . \tag{5}$$

The set of efficient portfolios is the solution of two equivalent problems,

$$\max_{w_i} E(\mathrm{R}_p) \ s.t. \sum_{i=1}^{s} w_i = 1, \sigma \leq \overline{\sigma}, \tag{6}$$

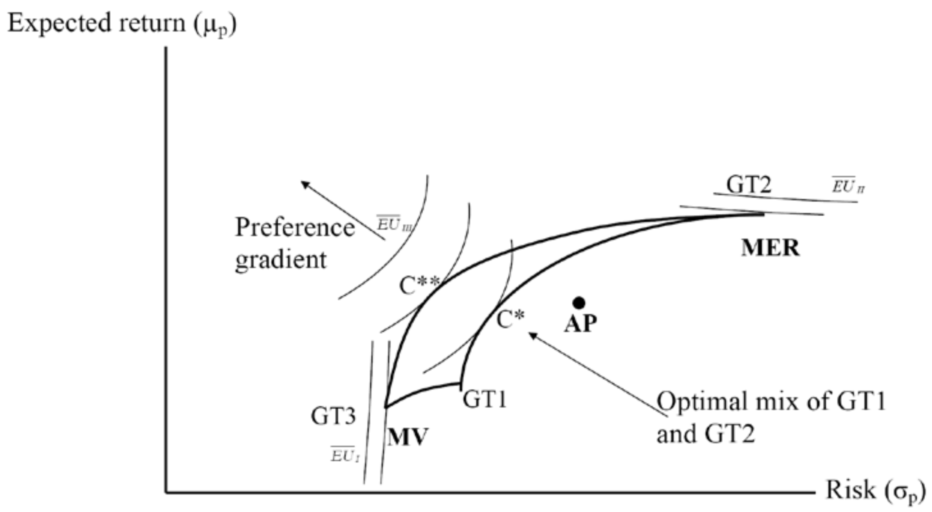
$$\min_{w_i} \sigma_p \ s.t. \sum_{i=1}^{s} w_i = 1, E(\mathrm{R}_p) \geq \overline{\mathrm{R}}. \tag{7}$$

Equation (6) says that the expected return of the portfolio is to be maximized subject to the constraint that volatility must not exceed a limit value $\overline{\sigma}$. Equation (7) says that volatility shall be minimized, whereas expected return cannot fall below a limit value $\overline{\mathrm{R}}$. In this study, the decision variables in both equations are the shares $w_i$ that are assigned to the generation technologies of the portfolio.

Portfolio theory determines an efficient frontier containing a continuum of positive solutions. The optimal solution depends on whether the investor or the current user view is adopted and on the degree of risk aversion.

In Figure 1, the horizontal axis depicts portfolio risk as measured by the standard deviation ($\sigma_p$), while the vertical axis displays expected return ($\mu_p$). The investor view is presented first. In that case, the vertical axis describes the percentage *change* of expected returns (measured in kWh/USD; the more positive, the larger the expected return).

**Figure 1:** Efficient portfolios of electricity generation technologies (GT)




To illustrate, let there be only two power electricity generation technologies, GT1 and GT2. By assumption, GT1 has little volatility in terms of change in expected returns; on the other hand, the expected change in expected return is small (e.g. *Coal* in the United States). By way of contrast, GT2 is more risky, but on expectation has higher return (e.g. *Wind* in the United States). Due to the correlation terms contained in eqs. (4) and (5), the efficient frontier linking GT1 and GT2 (i.e. combining the two technologies) is not linear but a segment of an ellipse. Thus, if the correlation between two electricity generation technologies is less than perfect $(-1 \leq \rho_{12} \leq 1)$, the efficient frontier between GT1 and GT2 runs concave from below. The lower the correlation coefficient, the stronger this portfolio effect[5]. This means that by adding GT2 with its high volatility but increasing expected return to the portfolio, the investor will profit from a diversification effect.

If returns of GT1 and GT2 move in a perfectly opposite way (i.e. $\rho_{12} = -1$), then a portfolio with no volatility at all can be constructed[6]. Such a portfolio always yields the same expected return, since whenever returns of GT2 are higher than expected, returns of GT1 are below expectation by an equal amount.

If a third technology (GT3) enters the portfolio, additional opportunities for diversification arise. However, to predict the optimal portfolio (to be selected among the efficient ones), knowledge of the investor's preferences would be necessary. This will not be the topic of this study per se; nevertheless, Figure 1 is complemented by the graphic representation of preferences

[5] Awerbuch (2006) argues that portfolio effects become more pronounced once correlation coefficients are below 0.6.

[6] Ingersoll (1987), chp. 4

using indifference curves, along which expected utility (EU) rather than utility is held constant since the presence of risk makes it impossible to attain a fixed level of utility.

Risk-averse investors like a higher expected return but dislike volatility. This means that the peak of an imagined hill of subjective valuation is way out on the vertical axis (implying a positive rate of return, but no volatility). Accordingly, the arrow symbolizing the direction of the peak (the so-called preference gradient) points northwest. Evidently, the optimum allocation of assets is given by the highest-valued indifference curve that is still compatible (i.e. tangent) with the efficient frontier. For the frontier composed of GT1 and GT2, this optimum is depicted by the tangency point C*. If GT3 is indeed available, C** becomes the new optimum, with a higher increase of the value of the portfolio and at the same time less volatility. Clearly, C** lies on a higher-valued indifference curve than C*, demonstrating the contribution to welfare that can be expected from the availability of additional energy technologies thanks to improved diversification.

Now the current user view is adopted, which characterizes decision-makers with a short-term planning horizon, arguably regulators and regulated utilities. In this case, the vertical axis describes expected returns in *levels* of kWh/USD (the higher the value, the larger the expected return). By assumption, GT1 (e.g. *Solar* generated power in Switzerland) has a low expected return but also a low volatility of expected return. By way of contrast, GT2 has much higher expected return but is more risky (e.g. *Run of river* in Switzerland). As before, a correlation between the two generation technologies that is less than perfect makes the efficient frontier run concave, resulting in a diversification effect[7]. In a study assessing the efficient electricity portfolio for Scotland, Awerbuch[8] showed that by adding *Wind* generation to the existing technology mix, a much lower standard deviation of the portfolio (with returns defined in kWh/USD) can be attained. This is because Scottish *Wind* generation costs (the inverse of returns) do not correlate with fossil fuel-intensive technologies, causing it to have a diversification effect[9].

In the following, focus will be on two extreme solutions, the minimum variance (MV) portfolio and the maximum expected return (MER) portfolio. The MV portfolio, which coincides with GT3 in Figure 1, is preferred by strongly risk-averse decision makers. The MER alternative, which coincides with GT2 in the example, is the option for (almost) risk-neutral types. These two portfolios permit to narrow down the efficient choices of both investors and current users. The gap between the actual portfolio AP and these two efficient portfolios indicates the scope of efficiency improvement. It also reflects foregone efficiency gains, which are to be related to the

[7] Awerbuch/Berger (2003)
[8] Awerbuch (2006)
[9] Awerbuch (2006) also refers to Brealey/Myers (1994), who illustrate that by adding riskless government bonds yielding as little as 3 percent to a stock portfolio yielding 8 percent serves to raise the expected return at any level of risk.

state of liberalization. Specifically, a liberalized electricity market is predicted to be closer to the efficiency frontier (smaller gap) than a regulated one, since regulation tend to consider a single generation technology at a time, rather than an efficient portfolio mix.

### 4.3.2 Seemingly unrelated regression estimation (SURE)

To derive time-invariant estimates of the covariance matrix (i.e. of $\sigma_i$ and $\sigma_{ij}$) predicted values of each time series of electricity-generating returns without a systematic shift are estimated by

$$\hat{\mathrm{R}}_{i,t} = \mathrm{R}_{i,t} - \hat{u}_{i,t} \; . \tag{8}$$

As has been shown in detail by Krey and Zweifel[10] shocks in the error term $u_{i,t}$ causing volatility in the dependent variable $R_{i,t}$ are correlated across technologies for both investors and current users. Therefore, the SURE (Seemingly Unrelated Regression Estimation) method is used to improve the efficiency of estimation, resulting in sharper estimates of the parameters and residuals, and hence of the $\sigma_i$ and $\sigma_{ij}$ making up the covariance matrix of returns.

The set of equations making up SURE in the three technology example read

$$\begin{aligned} \mathrm{R}_{1,t} &= a_0 + \sum_{j=1}^{m} a_{1,j} \cdot \mathrm{R}_{1,t-j} + u_{1,t} \\ \mathrm{R}_{2,t} &= b_0 + \sum_{j=1}^{m} b_{2,j} \cdot \mathrm{R}_{2,t-j} + u_{2,t} \quad , \\ \mathrm{R}_{3,t} &= c_0 + \sum_{j=1}^{m} c_{3,j} \cdot \mathrm{R}_{3,t-j} + u_{3,t} \end{aligned} \tag{9}$$

where $R_{1,t}, R_{2,t}, R_{3,t}$ are the returns for technologies *i*=1,2,3 in year *t*. $\alpha_0, b_0, c_o$ are their respective constants, $\alpha_{1,j}, b_{2,j}, c_{3,j}$ are the coefficients of returns lagged *j* years, $R_{1,t-j}, R_{2,t-j}, R_{3,t-j}$ are the dependent explanatory variables lagged *j* years, and $u_{1,t}, u_{2,t}, u_{3,t}$ are the error terms.

The crucial assumption of SURE is that the covariance matrix of residuals $\mathbf{\Omega}$ is not diagonal,

$$\mathbf{\Omega} = E(\mathbf{uu'}) = \begin{bmatrix} \sigma_{1,1} I & \sigma_{1,2} I & \sigma_{1,3} I \\ \sigma_{2,1} I & \sigma_{2,2} I & \sigma_{2,3} I \\ \sigma_{3,1} I & \sigma_{3,2} I & \sigma_{3,3} I \end{bmatrix} . \tag{10}$$

[10] Krey/Zweifel (2006)

Taking into account the possible correlation of error terms across equations, SURE simultaneously estimates the expected returns of all electricity-generating technologies in one set of regressions.

### 4.3.3 Data

U.S. and Swiss data on generating technology costs (the inverse of expected returns) comprise fuel costs, costs of current operations, capital user costs and an externality surcharge for environmental damage[11]. The U.S. data set covers five technologies, *Coal*, *Nuclear*, *Gas*, *Oil* and *Wind* power for the years 1981 to 2003. The Swiss data set consists of four variables, *Nuclear* for the years 1985 to 2003, *Run of river* and *Storage hydro* for 1993 to 2003, and *Solar*, covering the years 1991 to 2003. All variables are annual costs in changes (levels, respectively) in U.S. cents[12] per kWh electricity (inverse of expected returns), deflated by the CPI, with 2000 serving as the base year. Only annual aggregated data are available, representing more than 50 percent of capacity in both countries. Actual portfolios relate to the observed technology shares as of 2003 (see section 4.2), obtained from the International Energy Agency (IEA)[13] and the Swiss Federal Office of Energy (SFOE)[14]. Figures 2 and 4 show the AP2003 for the United States, Figures 3 and 5, that for Switzerland. For example, in 2003 *Coal* was the most prominent U.S. technology, with a share of 56 percent; in Switzerland, it was *Nuclear* with 40 percent.

## 4.4 Efficient U.S. and Swiss electricity-generating frontiers

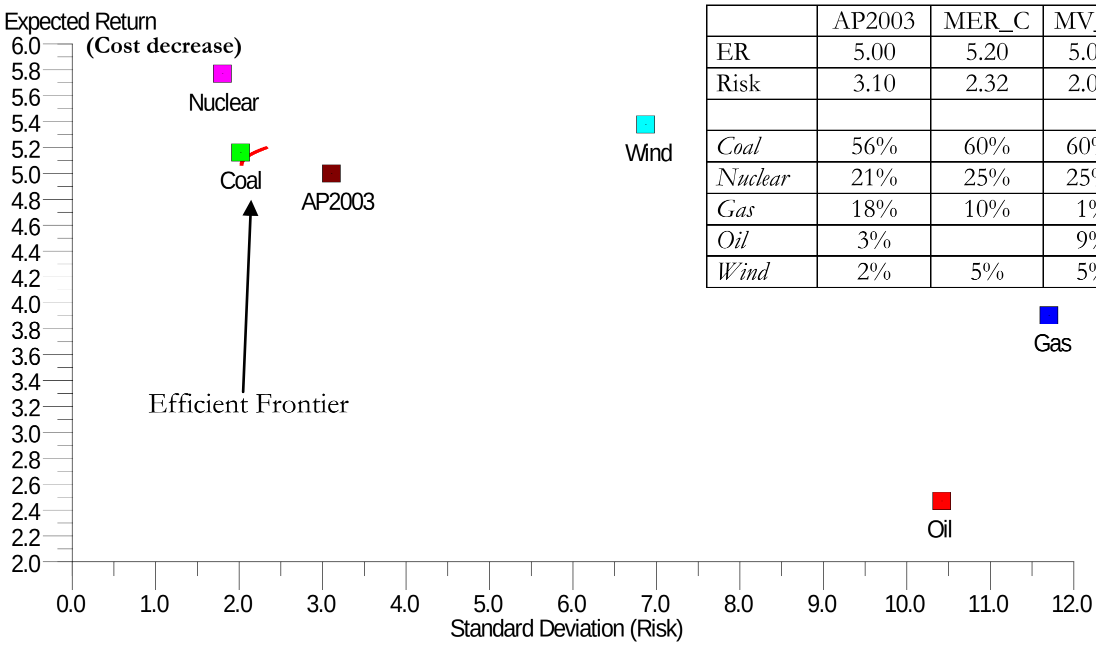
### 4.4.1 Efficiency frontier for the United States: Investor view

Figure 2 displays the feasible efficiency frontier for the United States adopting an investor view. To reflect technical feasibility[15], upper limits are imposed on technology shares. For example, the share of *Coal* cannot exceed 60 percent by assumption (see insert below Figure 2). The MER_C (with "C" for constrained) portfolio contains *Coal* (60 percent, binding, up from 56 percent in the actual portfolio), *Nuclear* (25 percent, binding, up from 21 percent), *Gas* (10 percent, down from 18 percent), and *Wind* (5 percent, binding, up from 2 percent). Compared to

[11] External cost data for the United States were approximated by data from the United Kingdom, which has a similar generation mix and structure (European Commission, (2003)).
[12] A conversion factor of USD 1 = CHF 1.65 was used (2003)
[13] IEA (2005); IEA (2006)
[14] SFOE (2004)
[15] Over the course of two decades and less, radical changes in the share of any single technology must be deemed unrealistic in view of the costs of adjustment implied.

the actual portfolio (AP 2003), the cost decrease would speed up (from 5.00 percent p.a. to 5.20 percent p.a.), while volatility would decline from 3.10 to 2.32 percent p.a.

**Figure 2:** Efficiency frontier for the United States
(2003, SURE-based, with constraints, investor view)




| | AP2003 | MER_C | MV_C |
|---|---|---|---|
| ER | 5.00 | 5.20 | 5.07 |
| Risk | 3.10 | 2.32 | 2.03 |
| | | | |
| *Coal* | 56% | 60% | 60% |
| *Nuclear* | 21% | 25% | 25% |
| *Gas* | 18% | 10% | 1% |
| *Oil* | 3% | | 9% |
| *Wind* | 2% | 5% | 5% |

**Constraints imposed:**
*Coal* ≤ 60%, *Nuclear* ≤ 25%, *Oil* ≤ 10%, *Wind* ≤ 5%

In the MV_C alternative, the highest share is allocated to *Coal*[16] (60 percent, binding), followed by *Nuclear* (25 percent, binding), *Oil* (9 percent, up from 3 percent), and *Wind* (5 percent, again binding). The only technology to lose market share is *Gas* (to a mere 1 percent, down from 18 percent). The rate of cost reduction would still attain 5.07 percent p.a. rather than 5.00 as in the actual portfolio, while risk declines to 2.03 from 3.10. Therefore, two important conclusions can be drawn. First, current U.S. power generation is inefficient from an investor point of view. Second, it could be made more efficient by substituting *Gas* by *Coal*, *Nuclear*, *Oil* (not in the MER_C portfolio), and *Wind*.

## 4.4.2 Efficiency frontier for Switzerland: Investor view

Figure 3 shows the efficient MER_C and MV_C electricity portfolios adopting an investor view for Switzerland. This time, *Storage hydro*, *Run of river*, and *Solar* are constrained to their actual shares in 2003 (32, 24, and 4 percent p.a., respectively, see insert below Figure 3), leaving only

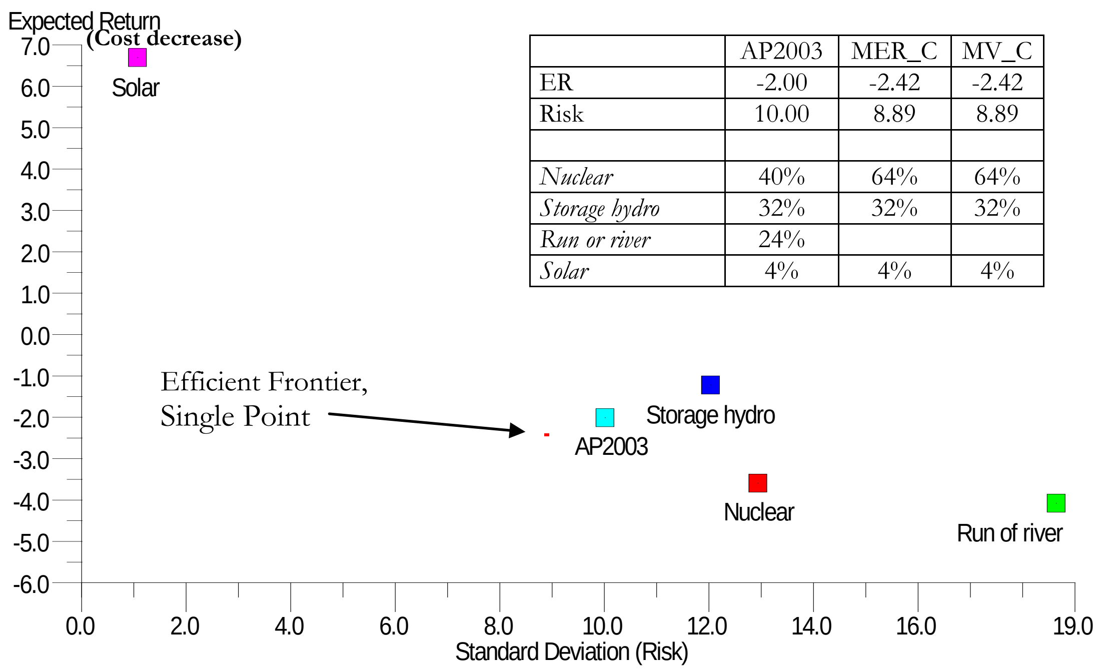
[16] Using portfolio theory for three U.S. generating technologies, Berger et al. (2003) also concluded that *Coal* dominates the MV portfolio taking a share of 77 percent.

*Nuclear* unconstrained. This can be justified because *Storage hydro* and *Run of river* are already utilized to full capacity[17], while a share of *Solar* electricity (a proxy for all renewables plus conventional thermic power plants and other sources) of 4 percent constitutes the limit of what could have been achieved.

Because the feasible efficient frontier shrinks to a single point, both MER_C and MV_C portfolios call for a complete substitution of *Run of river* (actual share 24 percent) by *Nuclear* (64 percent, up from 40 percent), *Storage hydro* (32 percent, binding), and *Solar* (4 percent, binding). *Run of river* has been subject to cost increases, which, combined with its poor diversification effect due to high correlations with other technologies, makes it an unattractive choice for an investor.

In all, Figure 3 suggests that even if "realistic" constraints are respected, Swiss electricity generation could be made more efficient (thus the 2003 mix is inefficient) by allowing the share of *Nuclear* to substantially increase while abandoning *Run of river*. Returns would fall at a slightly higher rate, from -2.00 (actual) to -2.42 percent p.a., regardless of choice between MER_C and MV_C portfolios, but volatility would drop from 10.00 (actual) to 8.89.

**Figure 3:** Efficiency frontier for Switzerland
(2003, SURE-based, with constraints, investor view)




| | AP2003 | MER_C | MV_C |
|---|---|---|---|
| ER | -2.00 | -2.42 | -2.42 |
| Risk | 10.00 | 8.89 | 8.89 |
| | | | |
| *Nuclear* | 40% | 64% | 64% |
| *Storage hydro* | 32% | 32% | 32% |
| *Run or river* | 24% | | |
| *Solar* | 4% | 4% | 4% |

**Constraints imposed:**
*Storage hydro* ≤ 32%, *Run of river* ≤ 24%, *Solar* ≤ 4%

[17] Laufer/Grötzinger/Peter/Schmutz (2004)

### 4.4.3 United States and Switzerland compared: Investor view

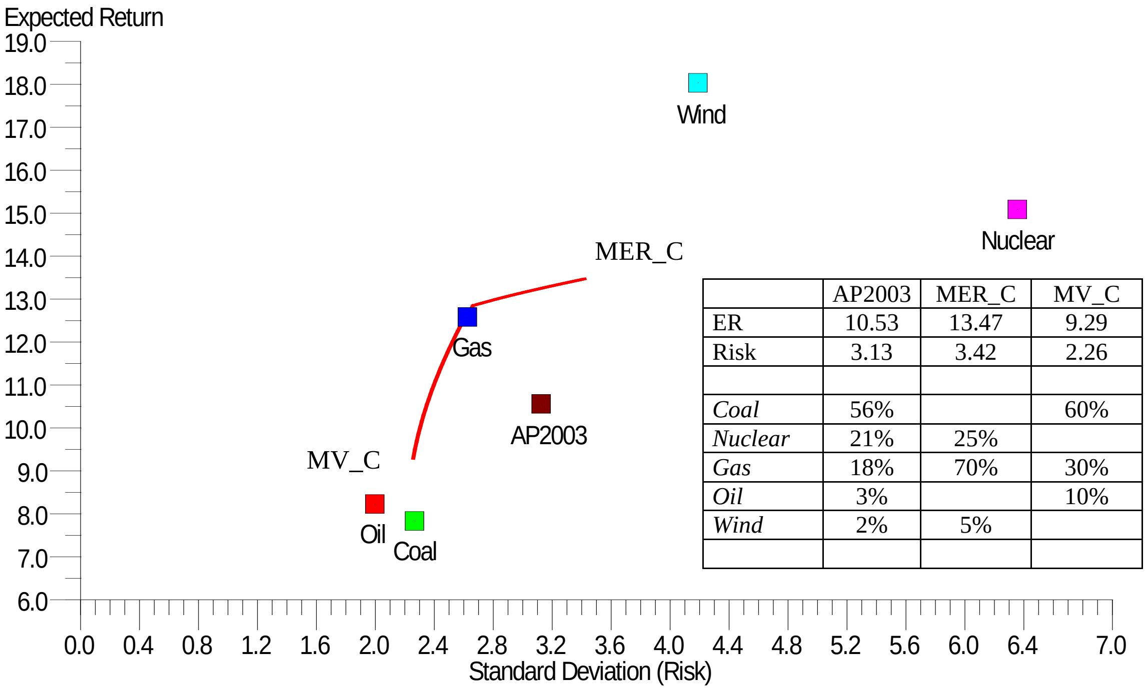
According to the feasible efficient portfolios, *Coal* in the United States and *Nuclear* in Switzerland are the principal sources for electricity generation. It appears that the U.S. electricity industry, while respecting feasibility constraints, would have gained by substituting *Gas* by *Coal*, *Nuclear*, and *Wind* technologies by 2003, regardless of the choice between the MER_C and the MV_ C portfolio. Swiss utilities would have stood to gain as well by adopting more *Nuclear* to the detriment of *Run of river*, an important source of primary energy until recently.

Therefore, both industries at present fall short of their respective efficiency frontiers. In the United States, the gap amounts to a foregone 0.07 to 0.20 percentage points p.a. of cost and 0.78 to 1.07 points volatility reduction (see Figure 2). In Switzerland, the estimates amount to a foregone 1.11 points reduction of risk (see Figure 3), which is larger than in the United States (between 0.78 and 1.07). However, the reduction in risk comes at the cost of a loss in expected return of 0.42 percentage points (in the United States, unit cost USD/kWh is falling and hence kWh/USD increasing). Therefore, a risk-averse U.S. investor would have gained by adopting the MV_C portfolio, a Swiss investor, possibly so. Interestingly, the evidence suggests that the scope of reducing risk in the more heavily regulated Swiss industry is bigger than in its largely deregulated U.S. counterpart.

### 4.4.4 Efficiency frontier for the United States: Current user view

For a current user of a technology, it is the return of a portfolio defined in kWh/USD that matters, and not its relative change (see section 4.3). Therefore, Figure 4 below displays the efficiency frontier for the United States in terms of levels. As before, constraints reflecting technical feasibility are imposed (see insert below Figure 4). The estimated MER_C mix contains *Gas* (70 percent, up from 18 percent), *Nuclear* (25 percent, binding, up from 21 percent), and *Wind* (5 percent, binding, up from 2 percent), leading to a large increase in expected return to 13.47 kWh/USD (rather than 10.53 in the AP2003) but also to higher risk (3.42 vs 3.13 kWh/USD). The MV_C portfolio on the other hand calls for *Coal* (60 percent, binding, up from 56 percent), *Gas* (30 percent) and *Oil* (10 percent, binding, up from 3 percent). This time, return falls from the AP2003 (10.53 kWh/USD) to 9.29. Risk is also reduced, from 3.42 to 2.26 kWh/USD. As can also be gleaned from Figure 4, the reduction in risk comes at the expense of a lower expected return.

**Figure 4:** Efficiency frontier for the United States
(2003, SURE-based, with constraints, current user view)




| | AP2003 | MER_C | MV_C |
|---|---|---|---|
| ER | 10.53 | 13.47 | 9.29 |
| Risk | 3.13 | 3.42 | 2.26 |
| | | | |
| *Coal* | 56% | | 60% |
| *Nuclear* | 21% | 25% | |
| *Gas* | 18% | 70% | 30% |
| *Oil* | 3% | | 10% |
| *Wind* | 2% | 5% | |
| | | | |

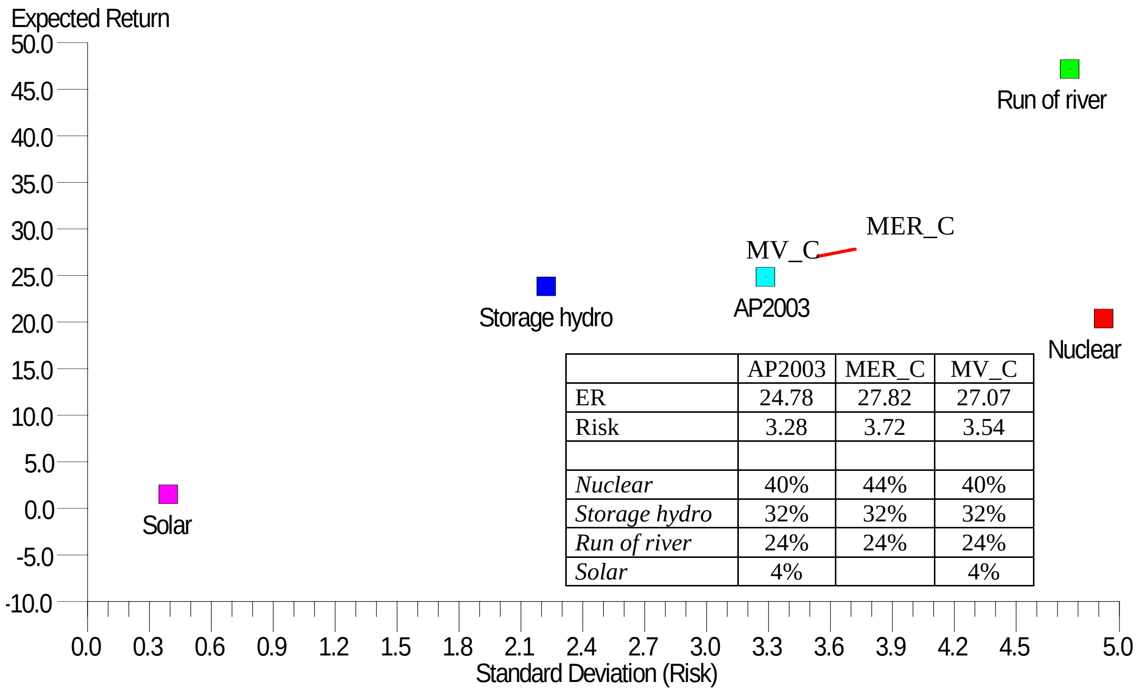
**Constraints imposed:**
*Coal* ≤ 60%, *Nuclear* ≤ 25%, *Oil* ≤ 10%, *Wind* ≤ 5%

## 4.4.5 Efficiency frontier for Switzerland: Current user view

Figure 5 displays the set of efficient power-generation portfolios for Switzerland defined in terms of kWh/USD. The same feasibility restrictions are imposed on the technology shares as in section 4.4.2 above.

Absent risk aversion, the MER_C portfolio would be preferred, containing *Nuclear* (44 percent, up from 40 percent), *Storage hydro* (32 percent, binding), and *Run of river* (24 percent, binding). Expected return is 27.82, compared to 24.78 kWh/USD in AP2003, while risk increases slightly from 3.28 to 3.72. The MV_C portfolio coincides with AP2003, with 40 percent *Nuclear*, 32 percent *Storage hydro*, 24 percent *Run of river*, and 4 percent *Solar*. Interestingly, it exhibits slightly more risk than AP2003 (3.54 as compared to 3.28 kWh/USD), which is due to the use of stabilized correlations in this particular instance. However, it has 2.3 percentage points more expected return (27.07 vs. 24.78), making it an attractive choice.

**Figure 5:** Efficiency frontier for Switzerland
(2003, SURE-based, with constraints, current user view)




| | AP2003 | MER_C | MV_C |
|---|---|---|---|
| ER | 24.78 | 27.82 | 27.07 |
| Risk | 3.28 | 3.72 | 3.54 |
| | | | |
| *Nuclear* | 40% | 44% | 40% |
| *Storage hydro* | 32% | 32% | 32% |
| *Run of river* | 24% | 24% | 24% |
| *Solar* | 4% | | 4% |

**Constraints imposed:**
*Run of river* ≤ 24%, *Storage hydro* ≤ 32%, *Solar* ≤ 4%

## 4.4.6 United States and Switzerland compared: Current user view

As before (investor view, see section 4.4.3) *Coal* takes the largest share in the U.S. MV_C portfolio. The big change is in the current user MER_C portfolio where now *Gas* dominates, while *Coal* is phased out. By way of contrast, *Nuclear* remains the principal source for Swiss electricity generation in both MER_C and MV_C portfolios. Once more, both countries fall short of their respective efficiency frontier. The United States faces a gap amounting to a foregone expected return increase of 2.94 kWh/USD in the MER_C portfolio and a foregone risk reduction of -0.87 in the MV_C mix (see Figure 4). In Switzerland, the estimates amount to a foregone expected return increase of 3.04 kWh/USD in the MER_C portfolio (0.10 kWh/USD more than in the United States). However, the larger increase in expected return comes at the price of an increase in risk in both MER_C and MV_C portfolios (see Figure 5). Risk-neutral current users would gain by adopting the MER_C portfolio in the United States. In Switzerland, they again stand to gain even more. This differential confirms the hypothesis that liberalization serves to enhance efficiency since Swiss electricity markets continue to be heavily regulated. However, this confirmation is incomplete because it is in the United States rather than Switzerland that risk-averse current users would benefit from adopting a feasible MV_C portfolio.

## 4.5 Conclusions

This paper employed Markowitz mean-variance portfolio theory to determine efficiency frontiers for electricity-generating technologies in the United States and Switzerland. Two perspectives were adopted. According to the investor view, expected returns are defined as *changes* in kWh/USD, while according to the current user view, they are defined as kWh/USD in *levels*. The observation period covers the years 1981 to 2003 (United States) and 1985 to 2003 (Switzerland).

The Seemingly Unrelated Regression Estimation (SURE) method was used to estimate a reasonably time-invariant covariance matrix. Since shocks in generation costs per kWh (the inverse of returns) are correlated, SURE serves to filter out the systematic components of the covariance matrix. Results suggest that the actual portfolios of generating technologies of the United States and Switzerland are off their respective efficiency frontiers. Both countries (but in particular Switzerland) could do better by rearranging their current portfolios.

Adopting the investor view, the United States are best advised to use more *Coal* and *Nuclear*. However, changes since 1985 have been in the right direction, likely fostered by early liberalization of electricity markets. As can be gleaned from Table 1 (Panel A), the share of *Nuclear* increased from 18 percent in 1985 to 21 percent in 2003, whereas the efficient value for risk-averse investors is 25 percent (see MV_C portfolio in Figure 2). In addition, the share of *Wind* increased from less than 0.01 percent in 1985 to about 2 percent in 2003 (the efficient value is 5 percent). However, the share of *Gas* did grow from 13.5 to 18 percent by 2003 while a mere 1 percent would be regarded efficient in this study. The observed value is much more in line with the current user view, which would prescribe 30 or even 70 percent (see Figure 4).

This should be contrasted with the Swiss experience. The share of *Nuclear* remained very stable between 39 to 40 percent between 1985 and 2003 (see Table 1, Panel B), whereas from an investor point of view (regardless of risk aversion, see Figure 3) it should be 64 percent. Likewise, the share of *Run of river* stayed between 24 and 25 percent whereas efficiency would have called for a phase-out. This continuity looks only efficient if the static current user view combined with tight feasibility constraints is adopted (see Figure 5). Of course, it is precisely this view that is typically compatible with regulation. The evidence therefore tends to support the hypothesis that U.S. producers and consumers of electricity benefited from liberalization, while their Swiss counterparts have to wait for a few more years to reap its benefits.

Future research may try to analyze more generating technologies, also taking into account imports of electricity, which can be considered as an additional component of the efficient technology portfolio. It would also be interesting to include more countries, among them a fully liberalized one, such as the United Kingdom.

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# Scope of Electricity Efficiency Improvement in Switzerland until 2035

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# Chapter 5

# Scope of Electricity Efficiency Improvement in Switzerland until 2035

## 5.1 Introduction

In this study, Markowitz mean-variance portfolio theory is applied to determine which electricity-generating technologies in Switzerland should be part of an efficient portfolio in 2035 in terms of maximizing expected return for any given level of risk or minimizing risk for any given level of expected return. By adopting a user view ("return" defined as kWh/CHF in levels), efficient technology mixes in 2035 are compared with the actual portfolio as of 2000 (AP2000) [1]. The gap between the two indicates the scope for efficiency improvement in terms of increasing expected return and/or reducing risk. In contrast, the European Union Energy Efficiency Action Plan (EEAP), which has been adopted in March 2007, uses a different efficiency improvement measure, viz. the maximum energy output for each unit of energy input. This approach, however, does not take any account of fluctuations in generation returns (risk), which arise due to volatile fuel costs and technological change. Therefore the adoption of a Markowitz mean-variance approach offers some additional insights.

Switzerland is expected to experience an electricity supply shortage between 20-40 percent by 2020, assuming a demand increase of 15-30 percent over 2000 (Gantner et al. 2000). As the government wishes to avoid an increased dependence on power imports, the options left are to generate more *Nuclear* electricity, introduce *Gas*-fired or new renewable technologies (such as *Solar*, *Smallhydro*, *Wind*, *Biomass*, and *Biogas*), or some mix of all these options. In fact, electricity suppliers such as Axpo and BKW but also organizations such as Avenir Suisse (an independent think tank for economic and social issues) in Switzerland are in favor of introducing new *Nuclear* power stations (see Meister, 2008), while *Gas* generated electricity (which has not been in use in

[1] Some contributions in this field of research adopt an investor view following the lead of Humphreys and McClain (1998). An investor is concerned about *changes* in value over time, viz. the percentage increase of expected return.

Switzerland so far) also enjoys some support. Other technologies, that are expected to contribute to the 2035 electricity mix, but which hold shares of less than 1 percent in the 2000 electricity mix, are *Smallhydro*, *Wind*, *Biomass*, *Incineration*, and *Biogas*.

In this study, efficient portfolios such as the maximum expected return (MER), same variance (SV), same expected return (SER), and minimum variance (MV) are also evaluated in terms of supply security, using Shannon-Wiener and Herfindahl-Hirschman indices. In addition, to select the best efficient portfolio amongst the four choices the Sharpe ratio is calculated, which measures return-to-risk ratios. Several future scenarios are considered, placing some emphasis on what seems politically and geologically feasible. Finally, SURE-based portfolios will be compared with portfolios that were calculated with OLS.

Results indicate that the feasible minimum variance (MV) portfolio displays the highest return-to-risk ratio, and should therefore be preferred over all other efficient portfolios. Risk-averse users are thus best advised to adopt a future (MV) portfolio mix containing 9 percent *Nuclear*, 20 percent *Run of river*, 13 percent *Storage hydro*, 5 percent *Solar*, 28 percent *Gas*, and 5 percent each of *Smallhydro*, *Wind*, *Biomass*, *Incineration*, and *Biogas*. In addition, OLS-based econometric model specifications generate different expected return and risk values for the actual portfolio (AP2000) than the SURE-based procedure. This indicates that the adoption of the right model specification is important.

The paper is organized as follows. Section 5.2 presents literature dealing with multiple generating technology portfolios and introduces key concepts of Markowitz mean-variance portfolio theory. This is followed by section 5.3 that describes the econometric methodologies applied to time series of generation returns. The data is presented in section 5.4. Section 5.5 displays the main results and considers two measures of supply security, viz. Shannon-Wiener and Herfindahl-Hirschman indices. Conclusions are offered in section 5.6.

## 5.2 Measuring multiple electricity-generating technology portfolios

An increasing number of studies have been published in the field of multi technology electricity-generating portfolios over the last few years. These studies can be broadly separated in three groups, stochastic optimization, maximum diversity portfolios and a much wider branch of literature dealing with Markowitz mean-variance portfolio theory. This section presents two studies in the field of stochastic optimization and maximum diversity portfolios. Section 5.2.1 explains the concept of Markowitz mean-variance portfolio theory in more detail.

Roques et al. (2006) use stochastic optimization to model dynamic power investment choices in the U.K. They use long-run stochastic trends in electricity, gas, and carbon prices based on current projections, where expected parameters are based on historical data and British and U.S. forecasts. Random trajectories for the electricity, gas, and carbon prices were drawn from a series of Monte Carlo simulations. Stochastic optimization was then used to estimate the option value to the generating company of keeping open the choice between nuclear and gas technologies. Roques et al. conclude, that for the higher discount rates (10 percent real) that could be expected for most private new nuclear plant constructions, nuclear option value represents 9 percent of the expected net present value cost of a nuclear plant investment when there is no correlation between electricity, gas, and carbon prices, but that this value falls sharply with increasing correlation between these prices. The nuclear option value is close to zero for the correlations observed in the U.K. in early 2000. According to Roques et al. (2006) these results imply that there is little value to electricity-generating companies in retaining the nuclear option in risky European electricity markets with the consequent high discount rates, given strong correlations between electricity, gas and carbon prices. Amongst others, Hlouskova et al. (2002) argue that stochastic optimization is very demanding in terms of computing with Roques et al. looking at only a 5-plant portfolio.

One way to overcome the computational limitations of stochastic optimization is to measure the best mix of electricity-generating technologies using so-called maximum-diversity portfolios as outlined by Stirling (1998). These portfolios take account of several performance criteria, disparity attributes, interactions, and constraints, where specific attributes such as political popularity are subjectively determined by the modeller. Performance criteria and disparity attributes are measured in ordinal categories (low, medium and high) which are again based on subjective opinions. In an application to the U.K. Stirling presents a maximum-diversity portfolio that suggests a mix containing a large share of gas, followed by coal and nuclear power. While the model appeals in terms of its complexity but ease of calculation, it clearly lacks in terms of objectivity. For example, Stirling claims that gas generated electricity in the U.K. is of high popularity to users, however, current market developments clearly speak against this view. In fact, sky-rocketing gas prices in the U.K. (an increase of more than 500 percent between January 2002 to January 2008, see Energy & Metals Consensus for Forecasts, 2008) underline the concern that the popularity of specific electricity generation technologies is subject to ongoing changes[1].

[1]Note, for example, that nuclear power after facing wide opposition for decades starts to enjoy an increasing popularity in Switzerland, which can be partly explained by increasing concerns about climate change, high fossil fuel and energy costs.

This paper therefore argues in favor of using Markowitz mean-variance portfolio theory, since it remedies all of the above-stated limitations, viz. it is straightforward to compute, takes account of all expected major generating technologies as of 2035, and covers the entire country's generation capacity using forecasted data.

## 5.2.1 Markowitz mean-variance portfolio theory

Mean-variance portfolio analysis, an established part of modern finance theory, is based on the pioneering work of Markowitz (1952), Varian (1993) and Fabozzi et al. (2002). In addition to its widespread use for financial portfolio optimization, mean-variance portfolio analysis has been applied to valuing offshore oil leases [Helfat (1988)], real asset portfolios in electricity generation [among others, Bar-Lev and Katz (1976), Adegbulugbe et al. (1989), Humphreys and McClain (1998), Awerbuch (2000), Awerbuch and Berger (2003), Berger (2003), Yu (2003), Awerbuch et al. (2004), Wenk and Madlener (2007), and Krey and Zweifel (2009)], and quantifying climate change mitigation risks [Springer (2003)]. This section outlines in more detail the theory of Markowitz mean-variance portfolio theory, and explains its use in this contribution.

In this study, mean-variance portfolio theory is used to locate efficient portfolios of electricity-generating technologies similar to Awerbuch et al. (2004). Risk is defined as the year-to-year variability (standard deviation) of expected return (kWh/CHF). Along the efficiency frontier, which will be explained in more detail in section 5.2.2, a Pareto improvement is not possible, since higher expected returns cannot be obtained without increasing the risk level, or, less risk cannot be generated without a reduction in expected returns. Efficient generating portfolios are thus defined by a twin property: they maximize expected return for any given level of risk or minimize expected risk for every level of expected return.

The following discussion of portfolio theory is based on a two-asset portfolio, presented in the context of portfolio return, viz. the inverse of generation costs.

Expected portfolio return $E(R_p)$ is the weighted average return of the generation mix components. For a two-technology generating mix, expected return is the weighted average of the individual expected returns of two technologies:

$$\text{Expected portfolio return: } E(R_p) = X_1 \cdot E(R_1) + X_2 \cdot E(R_2)\,, \qquad (1)$$

where $X_1$ and $X_2$ are the shares[2] of the two technologies in the mix and $E(R_1)$ and $E(R_2)$ are their expected electricity-generating returns.

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[2] here, $X_1+X_2=1$.

Portfolio risk, $\sigma_p$, is also a weighted average of the return variances of individual technologies:

$$\text{Portfolio risk: } \sigma_p = \sqrt{X_1^2\sigma_1^2 + X_2^2\sigma_2^2 + 2X_1X_2\rho_{12}\sigma_1\sigma_2}\,, \quad (2)$$

where $X_1$ and $X_2$ are the shares of the two technologies in the mix, $\sigma_1$ and $\sigma_2$ are the standard deviations of the expected return of the annual costs of technologies 1 and 2, and $\rho_{12}$ is the correlation coefficient of technologies 1 and 2.

Correlation affects the degree of diversification and hence the portfolio's overall risk. As can be seen in equation (3), if the correlation $\rho_{12}$ of the two technology example is zero, then expected total portfolio risk will always be lower than the same portfolio with identical technology shares and returns but with a positive correlation coefficient (see eq. 2). Obviously, once the correlation turns negative, risk can even be further reduced. In fact, if the correlation is -1, both technologies are perfectly negatively correlated, which implies that in a two technology portfolio where both technologies take the same shares, risk is completely diversified.

$$\text{Portfolio risk: } \sigma_p = \sqrt{X_1^2\sigma_1^2 + X_2^2\sigma_2^2}\,, \text{ if } \rho_{12} = 0\,. \quad (3)$$

To estimate the expected portfolio return and risk one therefore needs the individual expected returns $E(R_i)$, the individual standard deviations $\sigma_i$, the correlation coefficients between two technologies $\rho_{ij}$, and finally the technology shares $X_i$ of each individual technology in use. The individual expected returns and standard deviations on their own are not sufficient to determine their shares in the efficient portfolio. Therefore, technologies with low returns (viz. technologies with high costs[3]) can be part of an efficient mix if they diversify well.

## 5.2.2 Efficiency frontier

Figure 1 displays the theory as outlined in section 5.2.1, graphically (using data points based on the results presented in section 5.5). Expected return and risk of each generating technology are indicated by dots. For example, *Biogas* has a low expected return and low risk compared to *Nuclear*, which has a high expected return and high risk. Mean-variance portfolio theory is used to calculate the electricity-generating technology mix that is efficient. To do this all individual returns, standard deviations and their respective correlations between each technologies are taken into account (see eq. 1 and 2 for a two technologies example). There are infinite numbers of efficient portfolios, making up the efficiency frontier. Figure 1 displays a feasible efficiency frontier, feasible in the sense that no single technology can be the sole contributor to an efficient

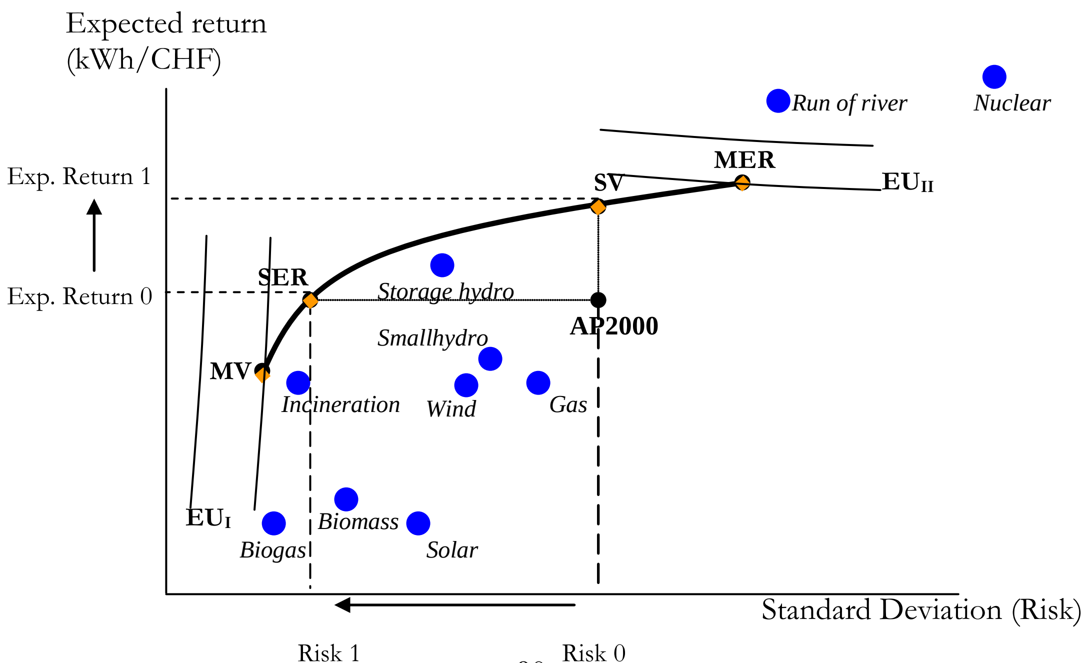
[3] Generation costs are the inverse of returns

portfolio due to pre-defined constraints. It seems unrealistic from a technological, political, and supply security view to assume that one single technology is the sole contributor of electricity in Switzerland. Thus, *Nuclear* and *Biogas* are not part of the feasible efficiency frontier, although they generate the highest expected return or lowest risk, respectively, on a stand alone basis.

This study focuses on four efficient portfolios in particular, the maximum expected return (MER) portfolio, the same variance (SV) portfolio, the same expected return (SER) portfolio, and the minimum variance (MV) portfolio. These four efficient portfolios are chosen, because the risk preference of the Swiss population is unknown. As can be seen by the indifference curves, risk-neutral users opt for the MER portfolio, while risk-averse users would prefer the MV portfolio. In fact, there are an infinite amount of efficient portfolios located along the efficiency curve, but to simplify the analysis only MER, SV, SER, and MV portfolios are considered.

The MER portfolio in 2035 contains only those technologies that maximize expected return, while risk is relatively high. Note that the efficient MER mix in Figure 1 generates considerably more expected return than the AP2000, however, this comes with relatively more risk. The SV portfolio in 2035 holds the technology mix that leads to the same risk as in 2000, but with more expected return (the gap between Exp. Return 0 and Exp. Return 1 on the vertical axis shows how much expected return can be gained by switching from the actual portfolio in 2000 to the efficient portfolio while holding the level of risk constant). The SER portfolio in 2035 generates the same expected return as in 2000, but with less risk (here the gap between Risk 0 and Risk 1 on the horizontal axis measures how much risk can be reduced if one switches from the actual generation mix to the efficient one while keeping expected returns constant).

**Figure 1**: Efficiency Frontier for Switzerland



For a country like Switzerland, where inhabitants are widely regarded as being risk-averse (Szpiro, 1986), the MV mix might be of greatest interest. The MV portfolio contains those technologies that minimize the standard deviation of the expected return (risk). Along an indifference curve, expected utility (EU) is held constant. The more the preference gradient points towards the expected return and away from the risk axis, the more marked is the user's risk aversion. Therefore, a risk-averse user would prefer the MV portfolio ($EU_I$), while a risk-neutral user would opt for the MER portfolio ($EU_{II}$).

### 5.2.3 Measures of return-to-risk

The Sharpe ratio (*SR*) is a measure of return-to-risk and can be used as an additional criterion to choose the best portfolio mix, viz. the one with the highest return-to-risk ratio. In this study, the *SR* is used to determine the best efficient portfolio within specific scenarios (see section 5.5.2). The ratio is defined as

$$SR = ER_p / \sigma_p , \tag{4}$$

where $ER_p$ is the expected return of the efficient portfolio (eq. 1) while $\sigma_p$ represents the volatility (measured as standard deviation of the expected return) of the efficient portfolio (eq. 2). A higher value of the Sharpe ratio (*SR*) is preferred over a lower one.

## 5.3 Econometric analysis

One important criterion to calculate efficient portfolios is the estimation of a stable variance/covariance matrix. If this is not the case the measure of risk, which is a main component to calculate efficient portfolios, will be erroneous. OLS and SURE specifications have been tried in this study, however, only the latter appears suitable to estimate the expected returns and standard deviations for the future portfolios for 2035 and the actual portfolio in 2000 (AP2000). First, a simple OLS specification was used. Consider equation 5, where generation costs $Y_{i,t}$ are explained by a constant $\beta_{i,0}$, autoregressive dependent variables $Y_{i,t-j}$, a time trend $Trend_i$ and the disturbance term $u_{i,t}$

$$Y_{i,t} = \beta_{i,0} + \sum_{j=1}^{m} Y_{i,t-j}\beta_{i,j} + Trend_i + u_{i,t} . \tag{5}$$

Shocks $u_{i,t}$ causing volatility in $Y_{i,t}$ are correlated across technologies. As a consequence the error variance/covariance matrix of the generation technologies is not orthogonal, which leads to biased estimation results of risk $\sigma^2$ (Wooldridge, 2003, p. 335).

SURE therefore appears to be superior to OLS because it takes account of error spillovers across equations.

## 5.3.1 Seemingly unrelated regression estimation (SURE)

The SURE approach provides estimates of the covariance matrix that are time-invariant. In each time series of electricity generation returns this calls for the estimation of predicted values

$$\hat{R}_{i,t} = R_{i,t} - \hat{u}_{i,t}, \tag{6}$$

that do not contain a systematic shift. However, such values cannot be calculated from eq. 5, since shocks in $u_{i,t}$ causing volatility in $R_{i,t}$ are correlated across technologies. As found by Krey and Zweifel (2006), if error terms are correlated, SURE offers a method to improve the efficiency of the estimation. The set of equations making up SURE in a four technology example, such as the actual portfolio for the year 2000, reads

$$\begin{aligned}
R_{1,t} &= a_0 + \sum_{j=1}^{m} a_{1,j} \cdot R_{1,t-j} + u_{1,t} \\
R_{2,t} &= b_0 + \sum_{j=1}^{m} b_{2,j} \cdot R_{2,t-j} + u_{2,t} \\
R_{3,t} &= c_0 + \sum_{j=1}^{m} c_{3,j} \cdot R_{3,t-j} + u_{3,t} \\
R_{4,t} &= d_0 + \sum_{j=1}^{m} d_{4,j} \cdot R_{4,t-j} + u_{4,t}
\end{aligned} \quad , \tag{7}$$

where $R_{1,t}$ to $R_{4,t}$ are the returns for technologies *i*=1,2,3,4 in year *t*. $a_0$ to $d_0$ are their respective constants, $a_{1,j}$ to $d_{4,j}$ are the coefficients of returns lagged *j* years, $R_{1,t-j}$ to $R_{4,t-j}$ are the dependent explanatory variables lagged $j$ years, and $u_{1,t}$ to $u_{4,t}$ are the error terms.

The crucial assumption that is specific to SURE is the non-diagonality assumption in the covariance matrix (see eq. 8), since it simultaneously estimates expected returns for all power generating technologies. This approach typically generates results that offer reliable estimates of the parameter $\beta_{i,j}$, residuals $u_{i,t}$, and hence of the $\sigma_i$ and $\sigma_{i,j}$ (covariance matrix).

$$\mathbf{\Omega} = E(uu') = \begin{bmatrix} \sigma_{1,1}I & \sigma_{1,2}I & \sigma_{1,3}I & \sigma_{1,4}I \\ \sigma_{2,1}I & \sigma_{2,2}I & \sigma_{2,3}I & \sigma_{2,4}I \\ \sigma_{3,1}I & \sigma_{3,2}I & \sigma_{3,3}I & \sigma_{3,4}I \\ \sigma_{4,1}I & \sigma_{4,2}I & \sigma_{4,3}I & \sigma_{4,4}I \end{bmatrix} \tag{8}$$

### 5.3.2 Measures of supply security

Shannon-Wiener and Herfindahl-Hirschman indices are calculated to evaluate the degree of diversification that is predicted by the efficient power generating portfolios. These indices shed light on the question whether the future supply of the efficient power generating portfolio mix as of 2035 is secure. In addition, Shannon-Wiener and Herfindahl-Hirschman indices show the trade-off between efficiency and security of supply that might arise. A system that relies on only a few technologies is exposed to collusion and monopoly. One measure of diversity is entropy, and can be calculated by the Shannon-Wiener Index

$$SW = \sum_{i=1}^{m} - p_i \ln(p_i), \tag{9}$$

where $p_i$ is the share of technology *i* in the efficient power generation portfolio. The weights of all technologies in the portfolio are considered ($i$=1,…,$m$). If the index exceeds the value of 1.00 the system is assumed to be well diversified and the risk of collusion or monopoly is low.

Alternatively, the Herfindahl-Hirschman index can be calculated. It is an alternative measure of security of supply and looks at the degree of concentration, in formal terms

$$HH = \sum_{i=1}^{m} P_i^2, \tag{10}$$

where $P_i$ is the share (in percent) of technology *i* in the efficient portfolio ($i$=1,…,$m$). No concentration, and thus security of supply is assumed if the values of $HH$<1800 basis points (bps) (Grubb et al., 2005).

## 5.4 The data

This study uses observed and predicted annual generation cost data[4], covering the periods 1991 to 2000 (to calculate the AP2000) and 2005 to 2035 (to estimate all future portfolios). Data were mainly obtained from Hirschberg (1999, 2005) and Oettli (2004) and relate to the returns of

[4] To obtain annual data, cubic spline interpolation was applied where necessary (Ingersoll, 1987).

*Nuclear*[5], *Run of river*[6], *Storage hydro*[7], *Solar power*[8], which were used to estimate the AP2000 and the future efficiency frontier, and *Gas*[9], *Biogas*, *Biomass*, *Incineration*, *Smallhydro* and *Wind* as additional technologies for the future[10] efficiency frontier estimation. All observations of electricity generation returns (kWh/CHF) are measured in levels (user view). Throughout, expected returns (the inverse of generation costs) comprise (i) fuel costs, (ii) costs of current operations, and (iii) capital user costs including depreciation. In the case of *Nuclear*, estimated decommissioning and waste disposal costs are also included. Externality surcharges are included since electricity generation causes hazards and environmental damage. Generation cost data for the period 1991 to 2000 is based on observed costs, and covers about 80 percent of all *Nuclear* power, and more than 60 percent of hydro power (*Run of river* and *Storage hydro*) capacities in Switzerland.

The data set for the period 2005 to 2035 was computed by Infras and is based on several assumptions, such as a constant population of 7.4 million people in Switzerland, economic growth of 1.5 – 2 percent per annum, a convergence of Swiss wages with the European average by 2025, and a real interest for capital costs of 2.5 percent (see Oettli et al., 2004). Generation costs, the inverse of expected returns, are predicted by using different scenarios[11] to estimate cost components such as fuel and fixed costs (including capital user costs). If different scenarios led to different cost predications, the higher priced generation cost components were chosen (conservative approach). Concerns may be raised about the predicted real interest rate for capital, since minor variations lead to great fluctuations in generation costs. The data set takes account of learning curve effects thus new-renewable technologies such as *Smallhydro* and *Wind* generate increasingly more expected return over time.

External costs are included and relate to health and global warming, which were obtained from Hirschberg and Jakob (1999). However, no data are available for some other categories, such as costs related to agriculture, forestry, and emission trading.

## 5.5 Portfolio estimation and discussion

This section presents the econometric results and predicted efficient electricity portfolios for Switzerland in 2035. For brevity, only the econometric results for the future portfolios are shown.

[5] Data sources: KKL (2005), KKG (2005), Hirschberg (2005, ch. 7) and Hirschberg and Jakob (1999, pp. 2-19).
[6] Data sources: personal correspondence, Hirschberg et al. (2005, ch. 4) and Hirschberg and Jakob (1999, pp. 2-19).
[7] Data sources: personal correspondence, Hirschberg et al.(2005, ch. 4) and Hirschberg and Jakob (1999, pp. 2-19).
[8] RWE Schott Solar (2005); The average exchange rate of 2000 was used to convert Euro into CHF (source: SNB). RWE Schott solar data from Germany is used as a proxy for Swiss solar electricity, since solar generation technologies are similar.
[9] At present Switzerland does not generate electricity with gas.
[10] By Infras, see Oettli et al. (2004).
[11] Scenarios looked at different degrees of electricity demand and electricity generation.

Correlation tables and regression results of the AP2000 estimation are presented in the appendix. The analysis compares the risk-return properties of the de facto 2000 generation mix to a set of efficient portfolios in 2035 using different scenarios. First, the discussion focuses on those portfolios that used correlations and a stable variance/covariance matrix estimated by SURE. Later, some results are compared with generated portfolios using correlations, expected returns and risk estimates obtained from OLS to see whether different model specifications lead to different efficient portfolio returns and risks and therefore generating technology shares.

## 5.5.1 Preliminary testing and SURE results

The augmented Dickey-Fuller (ADF) test confirms at the one percent significance level that all time series of returns are stationary (for both, the future and actual portfolio estimations). The correct lag order for the SURE regressions were obtained by using the following tests: Akaike's information criterion, Hannan & Quinn's information criterion, Schwarz's Bayesian information criterion and the likelihood ratio test (for details see Al-Sabaihi, 2002 and Liew, 2004). Table 3 further below displays the chosen lag orders for each technology in the future portfolio, Table A3 in the appendix shows the equivalent for the actual portfolio in 2000.

As mentioned before, SURE increases the efficiency of estimation by accounting for correlations in unobserved shocks. Table 1 provides evidence that supports this notion, which displays partial correlation coefficients that relate to returns (kWh/CHF).

**Table 1**: Partial correlation coefficients (2005 – 2035)

| **Technology** | ***Nuclear*** | ***ROR*** | ***Hydro Sto.*** | ***Solar*** | ***Gas*** |
|---|---|---|---|---|---|
| ***Nuclear*** | 1.0000 | -0.9165 | 0.1614 | 0.9628 | -0.9463 |
| ***Run of river*** | -0.9165 | 1.0000 | -0.4685 | -0.9820 | 0.9636 |
| ***Storage hydro*** | 0.1614 | -0.4685 | 1.0000 | 0.3847 | -0.3794 |
| ***Solar*** | 0.9628 | -0.9820 | 0.3847 | 1.0000 | -0.9752 |
| ***Gas*** | -0.9463 | 0.9636 | -0.3794 | -0.9752 | 1.0000 |
| ***Smallhydro*** | 0.8673 | -0.9931 | 0.5620 | 0.9593 | -0.9411 |
| ***Wind*** | 0.8668 | -0.9930 | 0.5626 | 0.9590 | -0.9408 |
| ***Biomass*** | 0.9675 | -0.9872 | 0.3684 | 0.9970 | -0.9772 |
| ***Incineration*** | 0.7199 | -0.9345 | 0.6740 | 0.8620 | -0.8416 |
| ***Biogas*** | 0.8597 | -0.9915 | 0.5662 | 0.9559 | -0.9374 |

| **Technology** | ***Smallhydro*** | ***Wind*** | ***Biomass*** | ***Incin*** | ***Biogas*** |
|---|---|---|---|---|---|
| ***Nuclear*** | 0.8673 | 0.8668 | 0.9675 | 0.7199 | 0.8597 |
| ***Run of river*** | -0.9931 | -0.9930 | -0.9872 | -0.9345 | -0.9915 |
| ***Storage hydro*** | 0.5620 | 0.5626 | 0.3684 | 0.6740 | 0.5662 |
| ***Solar*** | 0.9593 | 0.9590 | 0.9970 | 0.8620 | 0.9559 |
| ***Gas*** | -0.9411 | -0.9408 | -0.9772 | -0.8416 | -0.9374 |
| ***Smallhydro*** | 1.0000 | 0.9999 | 0.9641 | 0.9664 | 0.9995 |
| ***Wind*** | 0.9999 | 1.0000 | 0.9638 | 0.9666 | 0.9995 |
| ***Biomass*** | 0.9641 | 0.9638 | 1.0000 | 0.8691 | 0.9603 |
| ***Incineration*** | 0.9664 | 0.9666 | 0.8691 | 1.0000 | 0.9713 |
| ***Biogas*** | 0.9995 | 0.9995 | 0.9603 | 0.9713 | 1.0000 |

The coefficients indicate strong correlations. For example, *Incineration* and *Nuclear* exhibit a correlation of 0.7199. A very strong and negative correlation can be seen between *Run of river* and *Biogas* (-0.9915). Here, a one percent increase in returns for *Run of river* is matched by an almost identical drop in *Biogas*. Both technologies therefore diversify very well. A comparison of the same technologies for the time periods 1991-2000 (appendix, Table A1) and 2005-2035 (Table 1) reveals that *Nuclear* continues to diversify well with *Run of river* (in both time periods the coefficient stays negative). A strong negative correlation between these technologies seems intuitive, since a reduction in *Run of river* generated electricity (for example during a heat period) will be compensated by an increase in *Nuclear* generated power (*Nuclear* does not run on full capacity, and therefore has the ability to increase production capacity during times of electricity shortages). According to the forecasted data, this effect is expected to increase more than twice as much from -0.4945 for the time period 1991-2000 to -0.9165 between 2005-2035.

Table 2 contains the correlations of $u_{i,t}$, i.e. the residuals of eq. (7), which represent the components due to unobserved shocks. Correlation coefficients remain high, with no changes in signs. For instance, the correlation across the equations of *Incineration* and *Nuclear* is 0.7578. Partial correlations for the period 1991-2000 clearly differ (appendix, Table A2), here none of the coefficients are negative, and all exceed 0.95.

**Table 2**: Partial correlation coefficients for $u_{i,t}$ residuals from eq. (7) (2005 – 2035)

| Technology | *Nuclear* | *ROR* | *Hydro Sto.* | *Solar* | *Gas* |
|---|---|---|---|---|---|
| ***Nuclear*** | 1.0000 | -0.9398 | 0.0123 | 0.9690 | -0.9589 |
| ***Run of river*** | -0.9398 | 1.0000 | -0.2844 | -0.9848 | 0.9834 |
| ***Storage hydro*** | 0.0123 | -0.2844 | 1.0000 | 0.2171 | -0.2376 |
| ***Solar*** | 0.9690 | -0.9848 | 0.2171 | 1.0000 | -0.9854 |
| ***Gas*** | -0.9589 | 0.9834 | -0.2376 | -0.9854 | 1.0000 |
| ***Smallhydro*** | 0.8915 | -0.9914 | 0.4017 | 0.9622 | -0.9644 |
| ***Wind*** | 0.8912 | -0.9913 | 0.4024 | 0.9620 | -0.9642 |
| ***Biomass*** | 0.9784 | -0.9891 | 0.1883 | 0.9962 | -0.9886 |
| ***Incineration*** | 0.7578 | -0.9326 | 0.5666 | 0.8746 | -0.8785 |
| ***Biogas*** | 0.8907 | -0.9914 | 0.4016 | 0.9639 | -0.9649 |

| Technology | *Smallhydro* | *Wind* | *Biomass* | *Incin* | *Biogas* |
|---|---|---|---|---|---|
| ***Nuclear*** | 0.8915 | 0.8912 | 0.9784 | 0.7578 | 0.8907 |
| ***Run of river*** | -0.9914 | -0.9913 | -0.9891 | -0.9326 | -0.9914 |
| ***Storage hydro*** | 0.4017 | 0.4024 | 0.1883 | 0.5666 | 0.4016 |
| ***Solar*** | 0.9622 | 0.9620 | 0.9962 | 0.8746 | 0.9639 |
| ***Gas*** | -0.9644 | -0.9642 | -0.9886 | -0.8785 | -0.9649 |
| ***Smallhydro*** | 1.0000 | 0.9990 | 0.9645 | 0.9704 | 0.9996 |
| ***Wind*** | 0.9990 | 1.0000 | 0.9643 | 0.9706 | 0.9996 |
| ***Biomass*** | 0.9645 | 0.9643 | 1.0000 | 0.8736 | 0.9647 |
| ***Incineration*** | 0.9704 | 0.9706 | 0.8736 | 1.0000 | 0.9703 |
| ***Biogas*** | 0.9996 | 0.9996 | 0.9647 | 0.9703 | 1.0000 |

Table 3 displays the SURE regression results. As can be seen from the column denoted Exp. Return, *Nuclear* has the largest expected return, amounting to 25.7 kWh/CHF, while *Biogas* has the smallest expected return, at a mere 2.6 kWh/CHF. The standard deviations of all technologies vary widely, with *Biogas* being the least volatile (0.1) and *Nuclear* the most (4.7). Every regression includes a time trend, reflecting technological change, which is positive and significant for *Nuclear*, *Storage hydro*, *Smallhydro*, and *Wind*. These technologies are expected to continue to gain from technological progress (particularly learning effects), which lead to increases in expected returns over time. However, most of the coefficients are close to zero, indicating a slow rate of progress. The coefficients of determination $R^2$ all exceed 0.89 thus offering some confidence in the SURE results.

**Table 3**: Results of SURE regressions, Switzerland (2005 – 2035)

| Technology | Exp. Return | Std. dev | $b_0$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ | *Trend* | Obs | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Nuclear*** | 25.7 | 4.7 | -0.2*** | 2.8*** | -2.8*** | 0.9*** | - | 0.001*** | 27 | 0.90 |
| ***Run of river*** | 25.6 | 1.6 | 1.3** | 2.6*** | -2.3*** | 0.7*** | - | -0.01** | 27 | 0.89 |
| ***Storage hydro*** | 18.4 | 0.8 | 0.5*** | 3.2*** | -4.3*** | 2.7*** | -0.7*** | 0.001** | 27 | 0.89 |
| ***Solar*** | 3.1 | 1.2 | -0.003 | 3.1*** | -3.7*** | 2.0*** | -0.4*** | -0.0005 | 27 | 0.91 |
| ***Gas*** | 11.8 | 1.3 | 4.7*** | 0.7*** | - | - | - | -0.06*** | 27 | 0.90 |
| ***Smallhydro*** | 12.7 | 1.3 | 1.6*** | - | -0.8*** | 0.2 | 0.004*** | 0.3*** | 27 | 0.90 |
| ***Wind*** | 12.5 | 1.1 | 0.2*** | 1.7*** | -0.2 | -0.75** | 0.2 | 0.003*** | 27 | 0.92 |
| ***Biomass*** | 4.6 | 0.8 | -0.02*** | 2.7*** | -2.5*** | 0.8*** | - | -0.0002 | 27 | 0.99 |
| ***Incineration*** | 13.2 | 0.2 | 0.1 | 1.4*** | -0.4*** | - | - | -0.001*** | 27 | 0.89 |
| ***Biogas*** | 2.6 | 0.1 | -0.05 | 1.3*** | -0.25** | - | - | -0.001** | 27 | 0.95 |

*Significant at 10 percent level, ** significant at 5 percent level, *** significant at 1 percent level

As can be seen in the appendix (Table A3), *Run of river* and *Storage hydro* generate higher expected returns in 2000 than *Nuclear* power (30.1 and 15.1 vs. 14.4 kWh/CHF). One explanation for this is the inclusion of external costs (see section 5.4) that are higher for *Nuclear* power and thus lead to lower expected returns. In addition, decommissioning and waste disposal further reduce expected return for *Nuclear*. In addition, *Run of river* is the most volatile technology (2.7), which is due to seasonal variations in the quantity of water that is needed for power generation. The trend variable indicates that all four technologies in 2000 face increasing returns over time. With the exception of *Run of river* all $R^2$ results are comfortably high (all exceed 0.65).

## 5.5.2 Efficient portfolio shares for different scenarios using SURE

Three different future scenarios are examined, reflecting different degrees of feasibility constraints. Scenario SI contains no constraints, and therefore tends to generate concentrated technology portfolio mixes (see section 5.2.2). Along the efficiency frontier more diversified generation mixes are located, as will be seen in the cases of SV and SER portfolios. In scenario SII the shares of *Nuclear* and *Gas* are set to zero (reflecting a strict aversion to *Nuclear* power and *Gas* fuel dependency), while the shares of *Run of river* and *Storage hydro* cannot exceed 24 and 32 percent, respectively (this restriction is based on Laufer et al. (2004) who claim that larger shares of *Run of river* and *Storage hydro* are unlikely in the future due to technical and geological restrictions). Finally, scenario SIII presents a technologically feasible generation mix in accordance to studies by the Swiss Federal Office of Energy (SFoE, 2005) and Laufer et al. (2004). Here *Solar*, *Smallhydro*, *Wind*, *Biomass*, *Incineration* and *Biogas* are constrained to take a minimum share of 5 percent each, while *Nuclear*, *Run of river* and *Storage hydro* are constrained at maximum shares of 40 percent, 24 percent and 32 percent, respectively. The latter three technology constraints reflect the status quo view, where shares are kept the same in 2035 as in early 2000.

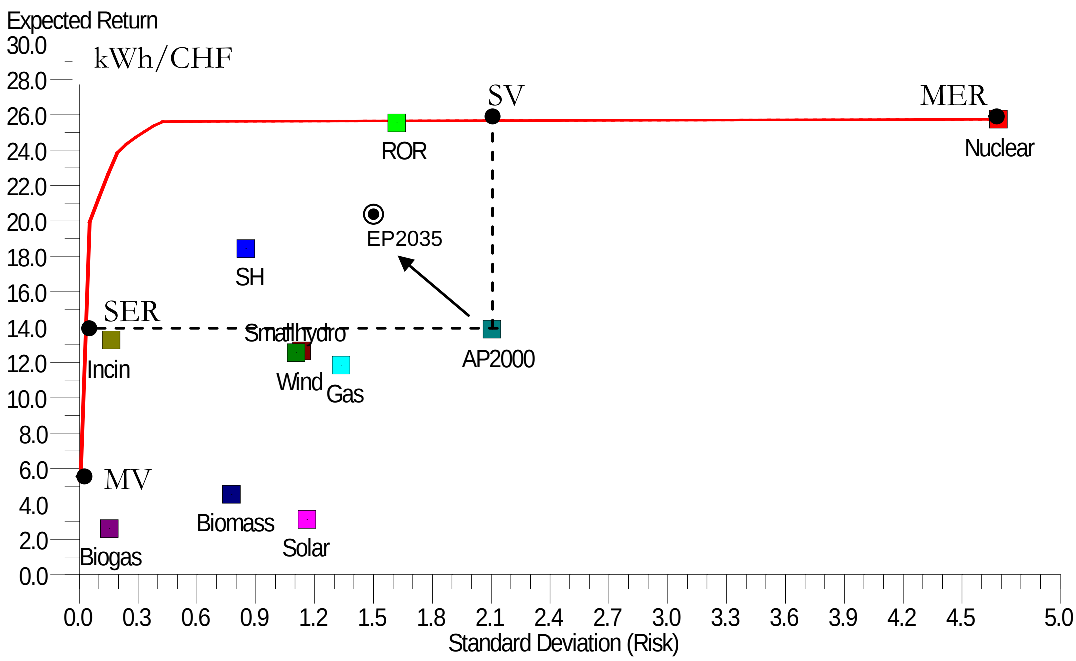
#### 5.5.2.1 Scenario SI: No constraints imposed

A look at Figure 2 reveals that the actual portfolio (AP2000) is far off the efficiency frontier, implying that the AP2000 mix is inefficient if no constraints are imposed (Scenario SI). As expected, the MER portfolio is heavily concentrated, containing 100 percent *Nuclear*, see Table 4. Expected return is almost twice the size of the AP2000 (25.74 kWh/CHF vs 13.82 kWh/CHF). Keeping risk the same (SV), a shift towards *Nuclear* (58 percent) and *Run of river* (42 percent) also improves expected returns to 25.67 kWh/CHF, which is only marginally less than the MER portfolio. On the other hand, the SER portfolio reveals how much risk can be reduced by keeping the expected return the same as in 2000. Using more *Run of river* (48 percent, up from 27 percent in AP2000) and *Smallyhdro* (42 percent, which has not been used before), while reducing the shares of *Nuclear* (7 percent, down from 38 percent) and *Storage hydro* (3 percent, down from 31 percent) decreases risk to a mere 0.05 (down from 2.10 in AP2000). Finally, the MV portfolio, containing a share of 88 percent *Biogas*, generates the lowest level of risk (0.01).

Shannon-Wiener and Herfindahl-Hirschman indices show that the inefficient AP2000 mix diversifies better than all four efficient portfolios. The *SW* index exceeds 1.00, which indicates that the risk of collusion is low. However, the *HH* index being more than 1800 bps signifies some concentration. With the exception of SER, all other portfolios are concentrated, with the MER taking the maximum possible *HH* index of 10000 bps, since the portfolio contains only one technology. According to the Sharpe ratio, the MV mix offers the best return-to-risk relationship, which is more than seventy times bigger than the AP2000 (529.00 vs. 7.00). Therefore, users are best advised to adopt the MV portfolio if they want a generating mix that offers the lowest risk and the highest return-to-risk ratio compared to the AP2000 and all other efficient portfolios.

If the same technology shares as in the AP2000 are adopted for the predicted year 2035 data set, then the portfolio shifts closer to the efficiency frontier as shown by portfolio EP2035 (see Figure 2). Here expected return increases from 13.82 in the AP2000 to 21.56 in EP2035. In addition, volatilities in returns are expected to decline from 2.10 as in AP2000 to 1.57 in EP2035. This shift could be explained by technological progress particularly due to learning curve effects (for example, expected return of *Solar* increases almost three times from 1.1 kWh/CHF in 2000 to 3.1 kWh/CHF in 2035, see Tables A3 and 3). However, this could also be due to the smoothing, which is inherent in forecasts.

**Figure 2**: Efficient portfolio for Switzerland using SURE procedure in scenario SI




However, because the EP2035 is based on the same technology shares as the AP2000 it can only be achieved if electricity consumption stays the same between 2000 and 2035, or if an increase in electricity demand is proportionately matched by an increase in all technologies. Both cases seem unlikely, because demand is expected to increase by at least 15 percent by 2020 (see section 5.1), and hydro generated electricity is already being fully utilized (Laufer et al. 2004).

Critics may also express their concern that scenario SI is generally unrealistic. In particular *Nuclear* and *Biogas* taking shares of 100 and 88 percent in the MER and MV portfolios, respectively, and *Run of river* exceeding 40 percent in the SER and SV portfolios are deemed unrealistic. Therefore the next two subsections discuss two additional scenarios, where so-called feasibility constraints are applied.

**Table 4**: Efficient Portfolio shares in Scenario SI

| | MER | SV | SER | MV | AP2000 | EP2035 |
|---|---|---|---|---|---|---|
| *Nuclear* | 100% | 58% | 7% | 1% | 38% | 38% |
| *Run of river* | | 42% | 48% | 10% | 27% | 27% |
| *Storage hydro* | | | 3% | | 31% | 31% |
| *Solar* | | | | | 4% | 4% |
| *Gas* | | | | 1% | | |
| *Smallhydro* | | | 42% | | | |
| *Wind* | | | | | | |
| *Biomass* | | | | | | |
| *Incineration* | | | | | | |
| *Biogas* | | | | 88% | | |
| **Exp. Return** | 25.74 | 25.67 | 13.82 | 5.29 | 13.82 | 21.56 |
| **Std.Dev.** | 4.69 | 2.10 | 0.05 | 0.01 | 2.10 | 1.57 |
| **SW** | 0.00 | 0.68 | 1.01 | 0.44 | 1.21 | 1.21 |
| **HH** | 10000 | 5138 | 4130 | 7814 | 3150 | 3150 |
| **Sharpe** | 5.49 | 12.22 | 276.41 | 529.00 | 7.00 | 14.00 |

### 5.5.2.2 Scenario SII: No nuclear and gas, restricted shares for hydro power

In scenario SII neither *Nuclear* nor *Gas* contribute towards an efficient electricity mix. Users that dislike *Nuclear* power and who strongly oppose any form of *Gas* dependency opt for this alternative. In addition, both hydro technologies are constrained to their technically feasible generation shares as predicted by Laufer et al. (2004). As can be seen in Figure 3, the efficiency frontier shrinks in size as compared to Figure 2 in 5.5.2.1[12], while the AP2000 is still far off the efficiency frontier. Table 5 shows that MER is much less concentrated than in the previous section. *Run of river* and *Storage hydro* take their binding shares, 24 and 32 percent, respectively. In addition, *Incineration* plays an important role (44 percent). Both expected return and standard deviation (risk) speak in favor of MER, since both values are better than the AP2000 ones, where expected return is 4 percentage points lower, and risk almost 2 percentage points higher. The efficiency frontier shrunk in size due to the imposed constraints. For that reason the SV portfolio could not be estimated. The SER portfolio mix contains 24 percent *Run of river* (binding share, down from 27 percent in the AP2000), and 12 percent *Smallhydro*, 26 percent *Biomass*, and 38 percent *Incineration*, which are all technologies, that if aggregated made up less than one percent before 2000. As before in scenario SI, the MV mix places a strong weight on *Biogas* (almost 80 percent), which helps to reduce risk to a mere 0.01. As can be seen by the Shannon-Wiener and Herfindahl-Hirschman indices, the SER portfolio displays some remarkable features: although *Nuclear* and *Gas* are not part of the efficient portfolio, the mix is very well diversified, much better than the inefficient AP2000 and all other efficient portfolio mixes. The same applies to the

[12] due to the imposed feasibility constraints

Sharpe ratio, no other portfolio in scenario SII exceeds 691.00. Therefore, in terms of expected return, *SW*, *HH* and the Sharpe ratio no other portfolio provides better results than the SER mix.

**Figure 3**: Efficient portfolio for Switzerland using SURE in scenario SII

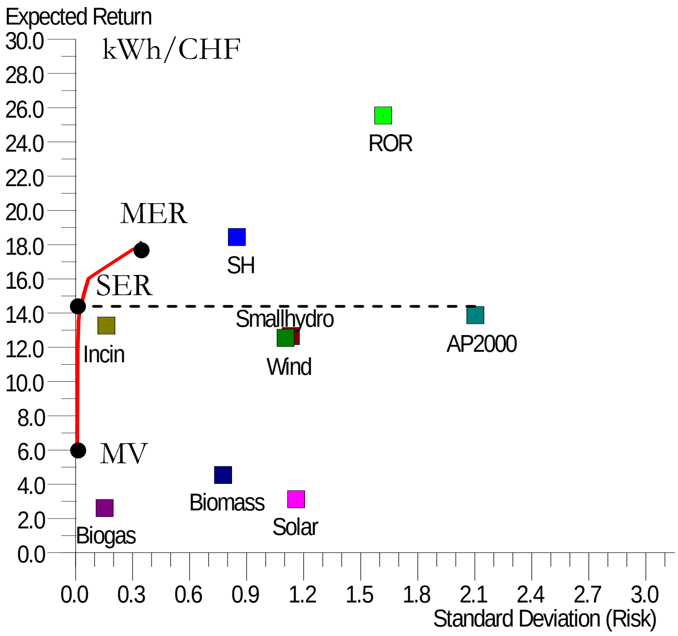



**Table 5**: Efficient portfolio shares in scenario SII

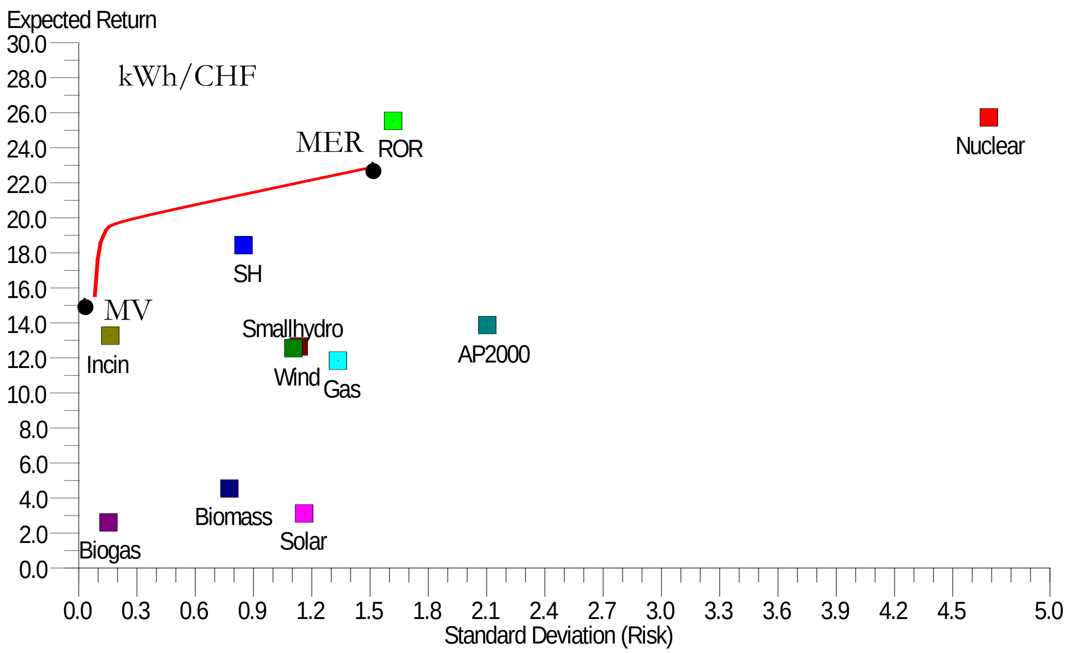
| | MER | SV | SER | MV | AP2000 |
|---|---|---|---|---|---|
| *Nuclear* | | | | | 38% |
| *Run of river* | 24% | | 24% | 12% | 27% |
| *Storage hydro* | 32% | | | | 31% |
| *Solar* | | | | | 4% |
| *Gas* | | | | | |
| *Smallhydro* | | | 12% | | |
| *Wind* | | | | | |
| *Biomass* | | | 26% | 12% | |
| *Incineration* | 44% | | 38% | | |
| *Biogas* | | | | 76% | |
| **Exp. Return** | 17.85 | | 13.82 | 5.70 | 13.82 |
| **Std.Dev.** | 0.37 | | 0.02 | 0.01 | 2.10 |
| **SW** | 1.07 | | 1.31 | 0.72 | 1.21 |
| **HH** | 3536 | | 2862 | 6067 | 3150 |
| **Sharpe** | 48.24 | | 691.00 | 570.00 | 7.00 |

### 5.5.2.3 Scenario SIII: Restricted shares for nuclear, hydro power, and new-renewables

In scenario SIII *Solar*, *Smallhydro*, *Wind*, *Biomass*, *Incineration* and *Biogas* take a minimum share of 5 percent each, while *Nuclear*, *Run of river* and *Storage hydro* are constrained to maximum shares of 40 percent, 24 percent and 32 percent, respectively. Figure 4 displays the efficiency frontier, which as before in Scenario SII shrunk in size, due to imposed feasibility constraints. As in the previous two scenarios, the AP2000 is off the efficiency frontier, indicating that an efficiency improvement is possible.

Table 6 shows, that the MER portfolio contains *Nuclear* (40 percent, constraint binding), *Run of river* (24 percent, constraint binding), *Storage hydro* (32 percent, constraint binding), and *Incineration* (4 percent). Like in section 5.5.2.2, the MER portfolio generates higher expected returns and less risk than the actual portfolio (AP2000). Due to the imposed constraints, both SV and SER portfolios are not part of the efficiency frontier, since the frontier shrunk in size. The MV portfolio contains all ten generating technologies, where *Gas*, *Run of river*, and *Storage hydro* contribute the largest shares, with 28 percent, 20 percent, and 13 percent, respectively. Both, expected returns and risk are more favorable in the MV portfolio than in AP2000.

**Figure 4**: Efficient portfolio for Switzerland using SURE in scenario SIII




As expected, the Shannon-Wiener index of the MV portfolio not only exceeds those of AP2000 and the efficient MER portfolio, but also those of all other *SW* indices that were previously calculated and displayed in Tables 4 and 5. The *HH* is below 1800 bps (the first, and only time in this study), indicating that this portfolio mix is secure and diverse. The Sharpe ratio is more than ten times larger than the MER, indicating that the return-to-risk relationship is best utilized with the MV portfolio. Therefore users in scenario SIII are best advised to adopt the MV portfolio, since it offers the highest expected return, the lowest risk, the best indices for security of supply and the highest return-to-risk ratio, relative to the inefficient AP2000 and the efficient MER portfolio.

**Table 6**: Efficient portfolio shares in scenario SIII

| | MER | SV | SER | MV | AP2000 |
|---|---|---|---|---|---|
| *Nuclear* | 40% | | | 9% | 38% |
| *Run of river* | 24% | | | 20% | 27% |
| *Storage hydro* | 32% | | | 13% | 31% |
| *Solar* | | | | 5% | 4% |
| *Gas* | | | | 28% | |
| *Smallhydro* | | | | 5% | |
| *Wind* | | | | 5% | |
| *Biomass* | | | | 5% | |
| *Incineration* | 4% | | | 5% | |
| *Biogas* | | | | 5% | |
| **Exp. Return** | 22.86 | | | 15.56 | 13.82 |
| **Std.Dev.** | 1.53 | | | 0.08 | 2.10 |
| **SW** | 1.20 | | | 2.06 | 1.21 |
| **HH** | 3216 | | | 1570 | 3150 |
| **Sharpe** | 14.94 | | | 194.50 | 7.00 |

## 5.5.3 Comparing OLS-based portfolios with SURE in scenario SIII

This section compares efficient portfolio technology shares that were determined by using different econometric specifications for scenario SIII. Although OLS estimates do not control for error spillovers across equations (see section 5.3) maximum expected return portfolios that are calculated by OLS (see Table 7) are the same as in scenario SIII where SURE is used (see Table 6).

**Table 7**: OLS-based scenario SIII

| | MER | SV | SER | MV | AP2000 |
|---|---|---|---|---|---|
| *Nuclear* | 40% | | | 10% | 38% |
| *Run of river* | 24% | | | 22% | 27% |
| *Storage hydro* | 32% | | | 13% | 31% |
| *Solar* | | | | 5% | 4% |
| *Gas* | | | | 25% | |
| *Smallhydro* | | | | 5% | |
| *Wind* | | | | 5% | |
| *Biomass* | | | | 5% | |
| *Incineration* | 4% | | | 5% | |
| *Biogas* | | | | 5% | |
| **Exp. Return** | 22.86 | | | 15.93 | 14.19 |
| **Std.Dev.** | 1.53 | | | 0.08 | 2.31 |
| **SW** | 1.20 | | | 2.07 | 1.21 |
| **HH** | 3216 | | | 1545 | 3150 |
| **Sharpe** | 14.94 | | | 200 | 6.14 |

Differences arise in the MV portfolio, where in SIII with SURE more weight is placed on *Gas* and less on *Run of river* as compared to OLS-based shares. Comparing expected returns of the AP2000 portfolios amongst SURE- and OLS-based portfolios reveals some striking differences. SURE-based AP2000 displays less expected return than OLS (13.82 vs. 14.19). The same holds true for the standard deviation, where SURE results are lower than OLS (2.10 vs. 2.31). The differences show that OLS-based portfolios tend to underestimate the scope of efficiency improvement, since differences between the future portfolios and the AP2000 are much smaller as compared to SURE-based portfolios. Therefore, controlling for the econometric methodology is important since correlated shocks in the disturbance term affect estimates of expected return and standard deviation.

## 5.6 Concluding comments

This study applied Markowitz mean-variance portfolio theory to determine efficient electricity-generating portfolios in Switzerland for 2035. These efficient portfolios were compared with the actual portfolio as of the year 2000 (AP2000). The gap between the AP2000 and the future efficient portfolios indicated the scope of efficiency improvement. OLS- and SURE-based econometric procedures were used to estimate a stable covariance/variance matrix of the technologies disturbance term. This is important to be able to obtain adequate expected returns and to derive reliable standard deviations, which are used to calculate efficient portfolios. However, OLS failed to account for error spillovers across equations, which has been remedied by using a Seemingly Unrelated Regression Estimation (SURE).

Three scenarios were analyzed, with feasibility constraints of different degrees of restrictiveness. According to the Sharpe ratio, viz. return-to-risk ratio, the MV portfolios score best in Scenarios SI (without constraints) and SIII (where constraints are imposed on *Nuclear*, *Run of river*, *Storage hydro*, and all new-renewables). In scenario SII (where both *Nuclear* and *Gas* generated electricity technology shares are set to zero, while both hydro technologies are restricted to feasible shares) the Sharpe ratio scored best with the same expected return (SER) portfolio, containing 24 percent *Run of river*, 12 percent *Smallhydro*, 26 percent *Biomass*, and 39 percent *Incineration.* This mix would suit users who dislike *Nuclear* power and any form of *Gas* fuel dependency.

According to Szpiro (1986) the Swiss population is best described as being risk-averse, therefore risk-averse (MV) power portfolio holders in 2035 (who do not oppose *Nuclear* and *Gas*) would be advised to adopt a feasible technology mix containing 28 percent *Gas*, 20 percent *Run of river*, 13 percent *Storage hydro*, 9 percent *Nuclear*, and 5 percent each of *Solar*, *Smallhydro*, *Wind*, *Biomass*, *Incineration*, and *Biogas*, respectively. This portfolio mix improves expected returns by more than 12 percent, while keeping risk more than 90 percent lower than the actual portfolio in 2000. The Shannon-Wiener and Herfindahl-Hirschman indices suggest that this mix is both secure and well diversified, and the Sharpe ratio is almost thirty times larger than that of the actual portfolio in 2000.

However, a share of 28 percent *Gas*, 5 percent *Biomass*, 5 percent *Incineration* and 5 percent *Biogas*, which move users closer to the efficiency frontier, entails additional $CO_2$ emissions. Therefore, if Switzerland is able to reposition its Kyoto emission reductions more towards transport fuels and away from electricity generation, this portfolio appears feasible.

The Energy Research Centre of the Netherlands (ECN) commissioned a similar application of portfolio analysis to the Dutch generating mix for 2030 (Jansen et al., 2006). Although the authors did not control for correlated shocks, their results point into the same direction as this study. Risk-averse electricity-generating technology portfolio holders in the Netherlands should adopt a mix in 2030 that contains 33 percent new-renewable technologies, such as *Wind* and *Biomass* (up from 6 percent in 2000). This mix comes at the expense of less *Nuclear* power (down to 0 percent from 5 percent in 2000), less *Coal* (down to 12 percent from 29 percent in 2000), and less *Gas* (down to 55 percent from 60 percent in 2000). Therefore, both countries, Switzerland and the Netherlands are advised to put more weight on new renewable technologies for at least two reasons: first, it reduces risk. Second, the generation portfolio is more diversified and thus serves well to ensure supply security.

One limitation of this study concerns the narrow focus on electricity-generating technologies. A wider perspective should include data on transportation and long-distance heating, which all play an important role in achieving a more efficient use of energy rather than only electricity. However, this study shows that Switzerland has scope for electricity-generating efficiency improvements by employing a more diversified portfolio mix containing *Nuclear* and *Gas*, combined with new-renewables.

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# Appendix

**Table A1**: Partial correlation coefficients (1991 – 2000)

| Technology | *Nuclear* | *ROR* | *Hydro Sto.* | *Solar* |
|---|---|---|---|---|
| *Nuclear* | 1.0000 | -0.4945 | -0.1488 | 0.9843 |
| *Run of river* | -0.4945 | 1.0000 | 0.5170 | -0.3856 |
| *Storage hydro* | -0.1488 | 0.5170 | 1.0000 | 0.0169 |
| *Solar* | 0.9843 | -0.3856 | 0.0169 | 1.0000 |

**Table A2**: Partial correlation coefficients for $u_{it}$ residuals (1991 – 2000)

| Technology | *Nuclear* | *ROR* | *Hydro Sto.* | *Solar* |
|---|---|---|---|---|
| *Nuclear* | 1.0000 | 0.9641 | 0.9812 | 0.9987 |
| *Run of river* | 0.9641 | 1.0000 | 0.9542 | 0.9532 |
| *Storage hydro* | 0.9812 | 0.9542 | 1.0000 | 0.9797 |
| *Solar* | 0.9987 | 0.9532 | 0.9797 | 1.0000 |

**Table A3**: Results of SURE regressions, Switzerland (1991 – 2000)

| Technology | Exp. Return | Std. dev | $b_0$ | $b_1$ | $b_2$ | $b_3$ | *Trend* | Obs | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| *Nuclear* | 14.4 | 2.2 | 4.8** | 0.3 | - | - | 0.36 | 10 | 0.75 |
| *Run of river* | 30.1 | 2.7 | 10.2 | -0.2 | 0.2 | 0.1 | 1.10** | 10 | 0.44 |
| *Storage hydro* | 15.1 | 1.8 | 8.3*** | -0.4** | 0.001 | -0.2 | 0.94*** | 10 | 0.68 |
| *Solar* | 1.1 | 0.2 | 0.02 | 0.4 | - | - | 0.04** | 10 | 0.99 |

*Significant at 10 percent level, ** significant at 5 percent level, *** significant at 1 percent level

**Table A4**: Partial correlation coefficients (2005 – 2035) using OLS

| Technology | *Nuclear* | *ROR* | *Hydro Sto.* | *Solar* | *Gas* |
|---|---|---|---|---|---|
| *Nuclear* | 1.0000 | -0.9399 | 0.0112 | 0.9689 | -0.9599 |
| *Run of river* | -0.9399 | 1.0000 | -0.2842 | -0.9853 | 0.9778 |
| *Storage hydro* | 0.0112 | -0.2842 | 1.0000 | 0.2167 | -0.2239 |
| *Solar* | 0.9689 | -0.9853 | 0.2167 | 1.0000 | -0.9829 |
| *Gas* | -0.9599 | 0.9778 | -0.2239 | -0.9829 | 1.0000 |
| *Smallhydro* | 0.8916 | -0.9914 | 0.4018 | 0.9628 | -0.9567 |
| *Wind* | 0.8912 | -0.9912 | 0.4025 | 0.9626 | -0.9565 |
| *Biomass* | 0.9784 | -0.9892 | 0.1876 | 0.9963 | -0.9858 |
| *Incineration* | 0.7593 | -0.9334 | 0.5662 | 0.8766 | -0.8675 |
| *Biogas* | 0.8912 | -0.9915 | 0.4012 | 0.9647 | -0.9577 |

| Technology | *Smallhydro* | *Wind* | *Biomass* | *Incin* | *Biogas* |
|---|---|---|---|---|---|
| *Nuclear* | 0.8916 | 0.8912 | 0.9784 | 0.7593 | 0.8912 |
| *Run of river* | -0.9914 | -0.9912 | -0.9892 | -0.9334 | 0.9915 |
| *Storage hydro* | 0.4018 | 0.4025 | 0.1876 | 0.5662 | 0.4012 |
| *Solar* | 0.9628 | 0.9626 | 0.9963 | 0.8766 | 0.9647 |
| *Gas* | -0.9567 | -0.9565 | -0.9858 | -0.8675 | -0.9575 |
| *Smallhydro* | 1.0000 | 0.9988 | 0.9646 | 0.9710 | 0.9996 |
| *Wind* | 0.9988 | 1.0000 | 0.9643 | 0.9712 | 0.9996 |
| *Biomass* | 0.9646 | 0.9643 | 1.0000 | 0.8748 | 0.9650 |
| *Incineration* | 0.9710 | 0.9712 | 0.8748 | 1.0000 | 0.9706 |
| *Biogas* | 0.9996 | 0.9996 | 0.9650 | 0.9706 | 1.0000 |

# Russian Gas to Western Europe: A Game-theoretic Analysis

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# Chapter 6

# Russian Gas to Western Europe: A Game-theoretic Analysis

## 6.1 Introduction

Russia is the most important supplier of gas worldwide and especially for Europe. At the time of the Soviet Union, transportation and routing was not an issue, since there was no third party involved. This changed when the Soviet Union collapsed. Newly independent states became indispensable parts of the Eurasian gas chain, causing a dramatic change for Russia. The transit countries, Ukraine and Belarus, seek to profit from their geographical location, while Russia wants cheap and reliable transport routes to sell its gas to Western Europe. This paper purports to determine the bargaining power of the three countries when negotiating over transit fees, taking account of new projects such as the Northern European Gas Pipeline (NEGP). However, it is also necessary to predict which of the possible coalitions will form. Estimated payoffs allow determining whether co-operation or independent optimization is the dominant strategy.

Early analysis of the gas supply game was performed by Grais & Zheng (1996), who modeled a Stackelberg game with Russia as the leader and Ukraine and Czechoslovakia as followers. A similar approach, with Belarus replacing Czechoslovakia as a transit country, was pursued by Hirschhausen v. et al. (2005), who developed cooperative and non-cooperative scenarios for different routes. Finally, Hubert and Ikonnikova (2003) analyzed the strategic behavior of the players, determining their bargaining power as indicated by the Shapley value.

The plan of this paper is as follows. After a description of the Eurasian gas chain and the objectives of the players in section 6.2, the transit game is modeled in section 6.3. Cooperative scenarios and bargaining power values derived are in section 6.3.1, while section 6.3.2 is devoted to non-cooperative scenarios. The data and calibrations follow in section 6.4, again for both the cooperative and the non-cooperative module. Optimal strategies for each player are explained and justified. The final section 6.5 contains a summary and concluding remarks.

# 6.2 The Eurasian gas chain

## 6.2.1 Historical development of transport routes

The former Soviet Union started delivering gas to Western Europe during the cold war, completing the first pipeline connection to Austria in 1968 and a second one to West Germany in 1973 (Stern, 2005). At that time, no independent countries stood between the producer and consumers. Pipeline Brotherhood went through Ukraine, which was part of the Soviet Union, to former Czechoslovakia, which was highly dependent on the Soviet Union (Hubert & Ikonnikova, 2004). The Soviet gas industry was a government agency whose actions were driven by politics (Hirschhausen v. & Engerer, 1998). A new export route in the North, from Belarus through Poland and East Germany, would have been economically viable, but Moscow decided that Czechoslovakia was politically more reliable than Poland.

After the collapse of the Soviet Union, Russia found itself in an unfavorable situation because its only export route to the West went through the newly independent states Ukraine, Slovakia, and Czech Republic, who inherited a quasi-monopolistic position for gas transit. Slovakia and the Czech Republic never capitalized on this fact because they were seeking integration into the European Union (EU) as reliable partners. Their segments of the pipeline were privatized quickly, with the Czech part bought by a consortium of German Ruhrgas, Gaz de France, and Russian Gazprom and the Slovakian part, by the German RWE. Ukraine, in contrast, was not a candidate for membership in the EU, permitting it to pursue its objectives independently. It received an in-kind transit fee and cheap gas from Russia. Problems arose when Ukraine started leaving its gas bills unpaid. It was also accused by Russia of stealing gas designated for export to Western Europe.

Both Russia and the EU had strong concerns about Ukraine's reliability and looked for alternative transit routes. The northern corridor through Belarus and Poland to Germany seemed to be the solution. Belarus was Russia's close ally, while Poland was vying for integration with the EU. In addition, Gazprom managed to buy into the Polish transit grid EuroPolGaz, on a par with Polish PGNiG. This paved the way for building the massive Yamal-Europe pipeline. While this project was repeatedly scaled down to become Yamal 1 with 18 bcm/a capacity (see Figure 1), it contains the option of building a second and third parallel pipeline, Yamal 2 and 3, for a total capacity of 56 bcm/a, 84 bcm/a, respectively (Hirschhausen v., 2003).

Increasing frustration with the transit countries led Russia to develop direct export routes. The first to be realized was the Blue Stream pipeline from Russia through the Black Sea to Turkey, causing Ukraine to lose its transit monopoly on the route to Southeast Europe. Transmission through Blue Stream started in 2003 with 2 bcm/a, to increase steadily to capacity (16 bcm/a) by 2010 (Gazprom, 2006). A direct pipeline between Russia and Germany through the Baltic Sea is the object of a joint venture between Gazprom (51 percent) and the German companies BASF (24.5 percent) and E.ON (24.5 percent) called the North European Gas Pipeline (NEGP) (named North Transgas in Figure 1). Construction works have already started in 2005 on the Russian side, with a planned capacity of 55 bcm/a. The first pipeline is expected to go on stream in 2010, providing 27.5 bcm/a capacity. Figure 1 shows existing and projected transport routes from Russia to Western Europe. The remainder of this section is devoted to a description of the players' objectives.

**Figure 1**: Russian gas and oil export routes to Western Europe


Source: EIA United States

## 6.2.2 Russia

Russian and Central Asian gas is landlocked and thus has to be transported by pipeline over long distances. The biggest gas fields are along the Ural and in Western Siberia, thousands of kilometers away form Western Europe. Other forms of transport, like LNG, CNG or the conversion of gas into chemical liquids or electricity are not technically mature. One ton of gas occupies more than thousand times the volume of one ton of oil and is therefore much more difficult and costly to transport (IFP, 2002).

Russian gas production is projected to reach 655 bcm in 2010 and 898 bcm by 2030. Russia will have to develop several new fields to compensate the production decline of its old giant fields while increasing total production. Russia's neighbors in the Caspian region, mainly Turkmenistan and Kazakhstan, have reserves amounting to some 8 trcm (=8,000 bcm), that are relatively easy to recover. Gazprom has already bought over 1 trcm of this gas under long-term deals, helping it to postpone the development of costly Russian fields to prevent them from exporting directly to Western Europe (IEA, 2004).

Gazprom is the world's largest gas company, responsible for over 90 percent of Russian gas production and wielding a monopoly for exports. It provides the most important source of governmental revenue, accounting for about 25 percent of the federal tax budget (Bruce, 2005). Gazprom was privatized in large part, causing it to pursue interests and goals different from those of the government. Former Russian president Putin's government stepped up its share in Gazprom and installed managers loyal to Moscow (todays new Russian president Medwedew used to be the chairman of the board of directors at Gazprom). Recognizing the importance of the transit routes, Gazprom has strived to achieve control over gas transit assets in Ukraine and Belarus, using unpaid gas bills and the threat of supply cuts to put pressure on the two countries (Bruce, 2005). In spite of this quest for power, Gazprom is hypothesized to pursue the maximization of its profits in the following.

### 6.2.3 Ukraine

Until recently, Ukraine has held a quasi-monopolistic position in the forwarding of Russian gas to Western Europe, the Balkans, and Turkey. During the 1990s, it accounted for more than 95 percent of Russian gas going to Western Europe, with the remainder passing through Belarus and Poland using low-pressure pipelines. Total westward transit capacity of Ukrainian pipelines is estimated at 100 bcm/a and southward capacity, at 40 bcm/a. Russia pays the transit fee in gas rather than money. While Ukraine has been seeking independence from Russia after the fall of the Soviet Union, it is unable to maintain and upgrade its pipelines without financial help from Russia and western countries. At the same time, it does not want to relinquish control over an essential facility that gives the country some power (Tyshchenko, 2002). In 2004, Russia and

Ukraine agreed to increase transit capacity by 19 bcm/a by 2010. On the whole, it is safe to assume that Ukraine tries to maximize revenue and therefore profits from gas transit.

### 6.2.4 Belarus

After the collapse of the Soviet Union, Belarus maintained strong ties with Russia. The common historical and cultural heritage suggests reunification, which however was never realized. Like all former Soviet republics, Belarus received cheap energy from Russia, even at a particularly low price that helped its economy but increased its dependency on Russia. In 2003, Belarus imported 18 bcm of Russian gas at a price of only $30/tcm, whereas Ukraine paid $50/tcm, and Western importers, over $100/tcm (Bruce, 2005). Belarus has negligible gas reserves, which makes it even more dependent on Russia than Ukraine (ENI, 2005).

Although Belarus offers the shortest, and therefore cheapest, reliable way to Western Europe, problems arose shortly after the opening of the new Yamal 1 pipeline. Belarus sought to increase its revenues from gas transit (Hubert & Ikonnikova, 2005). Moreover, like other transit countries it failed to pay fully for its gas from Russia. Russia and Gazprom tried to take control over the state company Beltransgaz by offering gas debt swaps, but without success. Accordingly, they lost interest in constructing the additional Yamal pipelines as originally planned. Another project, connecting the Yamal pipeline from Belarus through Poland and Slovakia in order to bypass Ukraine, is even more uncertain (Bruce, 2005). On the whole, assuming that Belarus uses its transit fees to maximize revenue seems to be justified.

## 6.3 The model

The crucial assumptions are the following. First, gas is assumed to be a homogeneous commodity, neglecting differences in quality e.g. between Russian and Dutch natural gas. Next, there is no collusion between Russia and other suppliers such as Norway. Third, for the transit countries Russia is the only purchaser of gas transit services. The market structure is thus a monopsony with very few suppliers of transit service, justifying the assumption of Cournot competition in the case of no cooperation.

The set of risk-neutral players consists of Russia, Ukraine and Belarus, to be symbolized by R, U, and B, respectively. The total amount of gas transported from the Russian border to Western Europe is denoted by $x_T$ no matter where it comes from. The quantities transported through Ukraine, Belarus, and the NEGP are $x_U$, $x_B$ and $x_N$ respectively, such that $x_T = x_U + x_B + x_N$. A linear demand function is assumed, following the lead of other authors (e.g. Hirschhausen v. et al. 2005). Western Europe is modeled as an aggregate of passive consumers in spite of EU attempts to organize an import cartel. Thus, its inverse demand function can be written $p = \alpha(x_T + x_{others}) + \beta$. In order to focus on gas from Russia, $x_{others}$ is viewed as exogenous. Demand for gas from suppliers other than Russia is therefore $b = a'x_{others} + \beta'$. In view of the assumed homogeneity of the product, $\alpha' = \alpha$ and $\beta' = \beta$, resulting in the follogiwng inverse demand function for Russian gas,

$$p = ax_T + b, \quad \text{with } a < 0,\ b > 0,\ dx_T/dp < 0. \tag{1}$$

Furthermore, let the cost of Russian gas production (including transport to its border) be constant at $c_R$. The per-unit cost of transport is also constant at $c_U$ and $c_B$ respectively, and $c_N$ through the NEGP. Since the number of players is taken as predetermined, barriers to entry are not at issue. Therefore, the costs of past and future pipeline construction are taken as sunk and will be neglected.

## 6.3.1 The cooperative module

The assumption is that some coalitions will form. Therefore, players' conditional payoffs need to be determined, which presumably depend on their bargaining power. Shapley values are calculated as in Hubert and Ikonnikova (2003), but with different assumptions and for different years. Additionally, Banzhaf values will be calculated. Both values are ex ante, predicting payoffs before it is known which players will cooperate.

The total number of players is denoted by n, equal to 3 in all cases considered here. Coalitions $K \leq n$ can be formed with $k \leq n$ players and payoffs v(K). Usually, a coalition's payoff also depends on the actions of excluded players. This does not apply here because Russia is an essential player, without whom no positive payoff can be realized. A coalition comprising Ukraine and Belarus does not form a complete supply chain, since they have no gas production of their own. The possible coalitions thus are {R,U,B}, {R,U}, {R,B}, {U,B} and the case where each player stands alone. The formula for the Shapley value is

$$\varphi_i(v) = \sum_{i \in K} \frac{(k-1)!(n-k)!}{n!} [v(K) - v(K \setminus \{i\})]. \tag{2}$$

This formula says that each player receives the average of its marginal contributions $v(K) - v(K\setminus\{i\})$, with $v(K\setminus\{i\})$ denoting the payoff achieved in player is absence. Players join randomly, making the probability of every sequence of players the same. Bargaining power $s_i$, is then obtained by calculating the relative contribution of a player (see section 6.4),

$$s_i = \frac{\varphi_i(v)}{\sum_{j=1}^{n} \varphi_j(v)}, \text{ with } \sum_{i=1}^{n} s_i(v) = 1. \tag{3}$$

The Banzhaf value $Z_i$ differs from the Shapley value in the following sense. Rather than assigning equal probabilities to sequences of players, it assigns equal probabilities to all possible coalitions. This seems more realistic in the present context, as tense political relations between all players do not favor any specific coalition. The Banzhaf value is thus given by

$$Z_i(v) = \frac{1}{2^{n-1}} \sum_{i \in K} [v(K) - v(K \setminus \{i\})] \;. \tag{4}$$

Bargaining power $h_i$ is calculated in analogy to equation (3),

$$h_i = \frac{Z_i(v)}{\sum Z_i(v)}. \tag{5}$$

Coalitions are assumed to maximize profits in keeping with section 6.3, given by

$$\Pi_K = \sum_{i=1}^{k} (p - c_i) x_i \,. \tag{6}$$

Optimal quantities of gas have to satisfy the constraints $0 \leq x_U \leq C_U$, $0 \leq x_B \leq C_B$, and $0 \leq x_N \leq C_N$, where e.g. $C_U$ stands for the capacity of Ukrainian transit pipelines.

In the case of the comprehensive coalition K={R,U,B}, the maximization problem reads,

$$\begin{aligned} \max_{x_U, x_B, x_N} \Pi_{R,U,B} = {} & [a(x_U + x_B + x_N) + b - c_R - c_U]x_U + [a(x_U + x_B + x_N) \\ & + b - c_R - c_B]x_B + [a(x_U + x_B + x_N) + b - c_N]x_N. \end{aligned} \tag{7}$$

A coalition with Russia and the Ukraine, K={R,U}, faces the maximization problem,

$$\max_{x_U, x_N} \Pi_{R,U} = [a(x_U + x_N) + b - c_R - c_U]x_U + [a(x_U + x_N) + b - c_N]x_N. \tag{8}$$

The corresponding formula for K={R,B} is

$$\max_{x_B, x_N} \Pi_{R,B} = [a(x_B + x_N) + b - c_R - c_B]x_B + [a(x_B + x_N) + b - c_N]x_N. \tag{9}$$

Russia is the only player who can establish a complete supply chain on its own in the future (beginning 2010). Its profit maximization problem then becomes

$$\max_{x_N} \Pi_R = [ax_N + b - c_N]x_N. \tag{10}$$

The capacity constraints and parameters of the demand functions change over the years, as will be shown in section 6.4.

## 6.3.2 The non-cooperative module

The objective of this section is to predict the payoffs given that players act in a non-cooperative manner. The game is super-additive with side payments since coalitions generate more profit than the sum of the single players' profits. Players can agree on side-payments, because payoffs, being in money (or money equivalents of gas), are transferable. They can choose to cooperate or not to cooperate. Thus, a player may not join a coalition but still participate in the game as an independent player. The choice variables are the quantities of gas on the different routes (for Russia) and the transit fees (for Ukraine and Belarus). For simplicity, the transit fee is paid in $/tcm by Russia rather than in gas.

At the beginning of the year considered, quantities and transit fees are set anew. There is perfect information about cost, demand, and bargaining power. With regard to Russia and the cost of the transit countries, this assumption is realistic since Russia built these transit pipelines or was involved in their construction. Therefore, Russia can act as a Stackelberg leader who takes into account the reaction functions of the transit countries. Once the transit fees and gas quantities are set, there is no renegotiation during the current period, and all parties fulfill their commitments.

The transit fee is the result of negotiations between Russia and the respective player. Russia's bargaining power is used to predict the outcome of the negotiation. Ukraine and Belarus, acting as independent, non-cooperative players, have the same type of maximization problem. For the Ukraine it reads,

$$\max_{t_u} \Pi_U = (t_U - c_U)x_U. \tag{11}$$

The FOC is

$$x^*_U + (t_U - c_U)\frac{\partial x_U}{\partial t_U} = 0\,, \tag{12}$$

because the amount of $x_U$ depends on $t_U$. In the following, define $\sigma := \partial x_U / \partial t_U = \partial x_B / \partial t_B < 0$, interpretable as Russia's bargaining power since σ shows how strongly it is able to respond to the respective transit fee. The response functions of Ukraine and Belarus therefore are

$$t_U^* = c_U - \frac{x_U}{\sigma} \text{ and} \tag{13}$$

$$t_B^* = c_B - \frac{x_B}{\sigma}. \tag{14}$$

The years considered are 2004, 2010, and 2030. The different constellations of players are (R\U\B), ({R,U}\B), ({R,B}\U) and (R\{U,B}), the grand coalition {R,B,U} was analyzed in section 6.3.1.

When deciding about the amount of gas to be exported, Russia presumably takes the marginal cost of transit along the different routes, $MC_U$, $MC_B$, and $MC_N$ into account. While $MC_N$ is constant, given by $MC_N = c_N - c_R \cdot MC_U$, marginal transit cost values $MC_B$ and $MC_B$ vary with $x_U$ and $x_B$, according to eqs. (13) and (14) unless Ukraine (Belarus, respectively) is in a coalition with Russia, in which case the transit country charges its marginal cost only. As the data from section 6.4 will show, Belarus has the lowest MC for small values of x, which are increasing in x. Thus, Russia is predicted to first use the pipelines through Belarus until $MC_B = MC_U$, then those of Belarus and Ukraine jointly, keeping their marginal costs equal, until $MC_U = MC_B = MC_N$. At that point, Russia shifts to NEGP with its constant marginal cost. If there should still be unmet demand beyond NEGP's capacity, Russia presumably distributes the remaining amount between Ukraine and Belarus, again keeping $MC_U = MC_B$. With total shipping cost to Russia given by $T = t^*_U \cdot x_U$, eqs. (13) and (14) imply that the equality of marginal cost $MC_U = MC_B$ calls for

$$c_U - \frac{2x_U}{\sigma} = c_B - \frac{2x_B}{\sigma}. \tag{15}$$

Therefore, one has

$$X^*_U = \frac{(c_U - c_B)\sigma + 2x_B}{2}, \text{ and } x^*_B = \frac{(c_B - c_U)\sigma + 2x_U}{2}. \tag{16}$$

In the case where none of the players cooperate, (R\U\B), the profit maximization problem for Russia is

$$\max_{x_U, x_B, x_N} \Pi_R = [a(x_U + x_B + x_N) + b - c_R - t_U]x_U + [a(x_U + x_B + x_N) + b - c_R - t_B]x_B$$
$$+ [a(x_U + x_B + x_N) + b - c_N]x_N \tag{17}$$

Taking the FOCs of (17) and using eqs. (13) and (14), one obtains

$$x^*_U = \frac{c_R + c_U - b - 2ax_B - 2ax_N}{2a + 2/\sigma}; \tag{18}$$

$$x^*_B = \frac{c_R + c_B - b - 2ax_U - 2ax_N}{2a + 2/\sigma}; \tag{19}$$

$$x^*_N = \frac{c_N - b - 2ax_U - 2ax_B}{2a}. \tag{20}$$

In the scenario ({R,U}\B), $MC_U = c_U = 5.14$ [see Hirschhausen v. et al. (2005)] is constant, since Ukraine being part of the coalition does not charge a profit-making transit fee. At the end of the period, Russia will transfer a certain share of its profits as a side payment, the value of which is not determined yet. Thus, Russia's profit maximization problem is

$$\max_{x_U x_B, x_N} \Pi_{R,U} = [a(x_U + x_B + x_N) + b - c_R - c_U]x_U + [a(x_U + x_B + x_N) + b - c_R - t_B]x_B$$
$$+ [a(x_U + x_B + x_N) + b - c_N]x_N . \tag{21}$$

Determining optimum values remains the same as before. Beyond the point where $MC_B = MC_U = 5.14$ is reached, Ukraine's pipelines will only be used to their capacity limit in view of their constant marginal cost. The FOC of (21) yield the same values for $x^*_B$ and $x^*_N$ as in eqs. (19) and (20). The only difference is Ukraine's amount,

$$x^{**}_U = \frac{c_R + c_U - b - 2ax_B - 2ax_N}{2a}. \tag{22}$$

In the case ({R,B}\U), it is Belarus that charges Russia a transit fee $t_B = c_B$. The decision problem for Russia then is

$$\max_{x_U, x_B, x_N} \Pi_{R,B} = [a(x_U + x_B + x_N) + b - c_R - t_U]x_U + [a(x_U + x_B + x_N) + b - c_R - c_B]x_B$$
$$+ [a(x_U + x_B + x_N) + b - c_N]x_N. \tag{23}$$

The transit capacity of Belarus will always be used up to its limit first because its marginal cost is lowest. Remaining demand is met through the Ukraine and NEGP. The FOC of (23) result in eqs. (18) and (20) for $x^{***}_U$ and $x^{***}_N$. For Belarus, one has

$$x^{***}_B = \frac{c_R + c_B - b - 2ax_U - 2ax_N}{2a}. \tag{24}$$

Finally, if the two transit countries form a transit coalition, $(R\backslash\{U,B\})$, they charge a uniform transit fee, $t_{UB}$. In turn, Russia decides on its own about the total amount of transit gas through these countries, $x_{UB} = x_U + x_B$, and the amount of gas through its own NEGP. The transit countries then allocate the gas to their pipelines. Knowing marginal costs, it is clear that the two transit countries use Belarus' pipelines first. The coalition's maximization problem then is

$$\max_{t_{U,B}} \Pi_{U,B} = (t_{UB} - c_U)x_U + (t_{UB} - c_B)x_B. \tag{25}$$

By taking the FOC as before, one obtains the new reaction function

$$t^*_{UB} = \frac{(c_U + c_B)\sigma - x_{UB}}{2\sigma}. \tag{26}$$

Russia's maximization problem then becomes

$$\max_{x_{UB},x_N} \Pi_R = [a(x_{UB} + x_N) + b - c_R - t_{UB}]x_{UB} + [a(x_{UB} + x_N) + b - c_N]x_N, \tag{27}$$

with FOC given by eq. (20) for $x^*_N$ and

$$x^*_{UB} = \frac{c_R + (c_U + c_B)/2 - b - 2ax_N}{2a + 1/\sigma} \tag{28}$$

The use of the different pipelines follows the same logic as above, with the capacity of the transit countries and to the point where $MC_{UB} = MC_N$, followed by a shift to NEGP.

## 6.4 Data and results

It is very difficult to obtain consistent and reliable data. Most figures, such as marginal transport cost and the demand function, are based on estimations. Even easily measured quantities such as transit capacities or volumes shipped do not seem to be known exactly in view of the wide range of figures published by analysts as well as the pertinent companies and institutions. In this situation, maximum values were retained.

Maximum effective pipeline capacities are presented in Table 1. The data for Ukraine refer to the total capacity of routes to Western Europe. Foreign investors are assumed to stay out; the increase in capacity between 2004 and 2030 therefore comes from upgrades, i.e. replacing old compressors by new ones. The data for Belarus contain the Yamal 1 pipeline (which as of 2008 has 18 bcm/a capacity) and low-pressure pipelines whose capacity is estimated at a constant 2 bcm/a. Expansion of Yamal 1 to 28 bcm/a can be expected by 2010, resulting in a total of 30 bcm/a. Depending on relationships with Russia, the development of alternative transport routes, and Western demand, Yamal 2 and 3 could be accomplished by 2030. At least Yamal 2 is likely to be constructed by 2030 because Belarus seeks to increase revenue from transit fees. Yamal 3 is also possible, provided foreign investors can be found. Both variants are entered in Table 1. Finally, NEGP will start in 2010 with a first pipeline. The second one can be expected to be ready by 2030, doubling capacity.

**Table 1:** Maximum westbound transit capacities in bcm/a

| Pipelines | 2004 | 2010 | 2030 |
|---|---|---|---|
| **Ukraine** | 100 | 120 | 120 |
| **Belarus** | 20 | 30 | 58/86 |
| **NEGP** | - | 27.5 | 55 |

Sources: Hirschhausen v. et al. (2005), Opitz & Hirschhausen v. (2000), NEGP (2006), Hubert & Ikonnikova (2005), Naftogaz (2006)

Marginal production and transport costs are taken as constant over time in real terms. On the one hand, development of new gas fields in difficult terrain might drive up marginal cost; on the other hand, technical progress reduced them in the past. Estimations are based on the report of OME (2002), which takes future developments into account. They are $c_R$ = 12.3 \$/tcm, $c_U$ = 5.14 \$/tcm, $c_B$ = 4.77 \$/tcm, and $c_N$ = 18.54 \$/tcm, taken from Hirschhausen v. et al. (2005). The demand function shifts outward over time, reflecting the fact that total demand is expected to increase further while Western Europe's own production will decline after the depletion of UK reserves (expected around 2010). The constant parameter over the years is $a = -0.789$. The outward shifting effect is created by an increase of b. Estimates are b = 141.1 \$/tcm for 2004, b = 220 \$/tcm for 2010 [which correspond to the scenario "demand expansion" in Hirschhausen v. et al. (2005)], and b = 260 \$/tcm for 2030, in keeping with a further increase in demand for Russian gas.

## 6.4.1 Results for the cooperative module

### 6.4.1.1 Postdictions for 2004

To obtain the solution for the comprehensive coalition, eq. (7) has to be maximized. This can be done in a simple, intuitive way, avoiding Kuhn-Tucker conditions. Since the marginal cost of transport through Belarus is lowest, routes through Ukraine will not be used unless Belarus reaches its capacity. Therefore, the first step is to take the FOC of (7) w.r.t. $x_B$ (assuming $x_U = 0$ for now), which gives

$$\frac{\partial \Pi_{R,U,B}}{\partial x_B} = 2ax_B + b - c_R - c_B = 0, \text{ implying} \tag{29}$$

$$x_B^{\ *} = \frac{c_R + c_B - b}{2a}. \tag{30}$$

When inserting the data of section 6.4 (see also Table A.1, in the appendix) in (30), one finds that $x^*_B > c_B$. Therefore, there is excess demand to be met by Ukraine. Knowing that, (7) can be differentiated w.r.t. $x_U$ to calculate $x^*_U$,

$$\frac{\partial \Pi_{R,U,B}}{\partial x_U} = 2ax_U + 2ax_B + b - c_R - c_U = 0, \text{ implying} \tag{31}$$

$$x^*_U = \frac{c_R + c_U - b - 2ax_B}{2a} \tag{32}$$

One obtains $x^*_B - c_B = 20$ bcm/a, $x^*_U = 58.365$ bcm/a, $x^*_T = 78.365$ bcm/a, $p^* = 79.27$ \$/tcm, and $\Pi^*_{R,U,B} = 4{,}853$ mn. \$. In the case of K = {R,U}, derivation of eq. (8) yield

$$x_U^{\ **} = \frac{c_R + c_U - b}{2a} \tag{33}$$

The results this time are, $x^{**}_U = 78.365$ bcm/a, $p^{**} = 79.27$ \$/tcm, and $\Pi^{**}_{R,U} = 4{,}845$ mn. \$. Finally, the solution for K = {R,B} is

$$x^{***}_B = \frac{c_R + c_B - b}{2a}. \tag{34}$$

In this case, the capacity limit is reached again so that $x^{***}_B = 20$ bcm/a, $p^{***} = 125.32$ \$/tcm, and $\Pi^{***}_{R,B} = 2{,}165$ mn. \$.

To calculate the Shapley and the Banzhaf values, Table 2 is useful. MB stands for the marginal contribution of a player to a coalition in a sequence of accession ρ, which depends on the player's position in the sequence. Bargaining power can then be calculated from eqs. (2), and (3), and (4), and (5), respectively. Although the Banzhaf value is deemed more appropriate, it differs but little from the Shapley counterpart. Both values agree in that Russia dominates not only the other two countries individiually but even jointly.

**Table 2:** Marginal contributions, Shapley value and Banzhaf value (2004)

| Sequence ρ | $MB_R$ (ρ) | $MB_U$ (ρ) | $MB_B$ (ρ) | Sum ($ mn.) |
|---|---|---|---|---|
| **(R, U, B)** | 0 | 4,845 | 8 | 4,853 |
| **(R, B, U)** | 0 | 2,688 | 2,165 | 4,853 |
| **(U, R, B)** | 4,845 | 0 | 8 | 4,853 |
| **(U, B, R)** | 4,853 | 0 | 0 | 4,853 |
| **(B, R, U)** | 2,165 | 2,688 | 0 | 4,853 |
| **(B, U, R)** | 4,853 | 0 | 0 | 4,853 |
| **Sum** (=Shapley value after multiplication by (1/n!) | 16,716 | 10,221 | 2,181 | 29,118 |
| **Bargaining power** (Shapley value) | 0.574 | 0.351 | 0.075 | 1 |
| **Bargaining power** (Banzhaf value) | 0.561 | 0.341 | 0.098 | 1 |

### 6.4.1.2 Predictions for 2010

As before, the cheapest alternative will be used up to its limit before using the next one in the order of merit. Thus, for K = {R,U,B}, Belarus will be used, followed by Ukraine and, given demand, by the now available NEGP. Using (30) and (32) and plugging in the figures from Table A.1, one can see that the capacity of Belarus is fully used. However, Ukraine's capacity limit is not reached, leaving NEGP idle. The results are: $x^*_B = 30$ bcm/a, $x^*_U = 98.37$ bcm/a, $x^*_N = 0$ bcm/a, $p^* = 118.72$ $/tcm, and $\Pi^*_{R,U,B} = 13{,}012$ mn. $.

In the case K = {R,U}, Ukraine's capacity will be used before Russia's own. Putting the relevant figures into (34) shows that Ukraine's capacity is not sufficient to satisfy demand. Therefore, excess gas has to be transported through the NEGP. It is calculated from

$$\frac{\partial \Pi_{R,U}}{\partial x_N} = 2ax_N + b - c_N + 2a\,x_U = 0, \qquad \text{implying} \tag{35}$$

$$x^{**}_N = \frac{c_N - b - 2ax_U}{2a}. \tag{36}$$

In all, the results are $x^{**}_U = 120$ bcm/a, $x^{**}_N = 7.67$ bcm/a, $p^{**} = 119.27$ $/tcm, and $\Pi^{**}_{R,U} = 12{,}992$ mn. $. The outcome for K = {R,B} is calculated in analogous manner. The capacity of Belarus turns out not be enough to meet demand. To calculate the quantity allocated to NEGP, one forms the pertinent FOC,

$$\frac{\partial \Pi_{R,B}}{\partial x_N} = 2ax_N + b - c_N + 2a\, x_B = 0, \text{ implying} \tag{37}$$

$$x_N^{***} = \frac{c_N - b - 2ax_B}{2a}. \tag{38}$$

The results show that the NEGP capacity limit is exceeded as well, hence $x^{***}_B = 30$ bcm/a, $x^{***}_N = 27.5$ bcm/a, $p^{***} = 174.63$ bcm/a, and $\Pi^{***}_{R,B} = 9{,}019$ mn. \$. For Russia alone, differentiating (10) yields

$$\frac{\partial \Pi_R}{\partial x_N} = 2ax_N + b - c_N = 0, \text{ implying} \tag{39}$$

$$x_N^{\circ} = \frac{c_N - b}{2a}. \tag{40}$$

The outcomes are therefore $x_N^{\circ} = 27.5$ bcm/a, $p^{\circ} = 198.3$ \$/tcm, and $\Pi_R^{\circ} = 4{,}943$ mn. \$, taking account of the capacity constraint. The values for bargaining power can be calculated as before. The results for 2010 are presented in Table 3. As expected, both indicators point to an increase of Russia's bargaining power compared to 2004 (see Table 2), mainly to the detriment of Ukraine.

**Table 3:** Bargaining power (2010)

| | Russia | Ukraine | Belarus | Sum |
|---|---|---|---|---|
| **Bargaining power** (Shapley value) | 0.742 | 0.205 | 0.053 | 1 |
| **Bargaining power** (Banzhaf value) | 0.712 | 0.215 | 0.073 | 1 |

#### 6.4.1.3 Predictions for 2030

The calculations are analogous to the ones for the year 2010. Assuming that Belarus completes only the Yamal 2 (Variant 1), they are for K = {R,U,B}, $x^*_B = 58$ bcm/a, $x^*_U = 95.7$ bcm/a, $x^*_N = 0$ bcm/a, $p^* = 138.72$ \$/tcm, $\Pi^*_{R,U,B} = 18{,}664$ mn.\$; For K = {R,U}, one obtains $x^{**}_U = 120$ bcm/a, $x^*_N = 33.02$ bcm/a, $p^{**} = 139.27$, $\Pi^{**}_{R,U} = 18{,}606$ mn.\$. For K = {R,B}, the values are $x^{***}_B = 58$ bcm/a, $x^{***}_N = 55$ bcm/a, $p^{***} = 170.84$ \$/tcm, $\Pi^{***}_{R,B} = 17{,}295$ mn.\$. Finally, for K = {R}one has $x_N^{\circ} = 55$ bcm/a, $p^{\circ} = 216.6$

$/tcm, $\Pi_R^{\circ}$ = 10,893 mn. $. The associated values of bargaining power are displayed in Table 4. Russia's position improves even more than in 2010, again to the detriment of Ukraine.

**Table 4:** Bargaining power (2030, Variant 1)

| | Russia | Ukraine | Belarus | Sum |
|---|---|---|---|---|
| **Bargaining power** (Shapley value) | 0.849 | 0.093 | 0.058 | 1 |
| **Bargaining power** (Banzhaf value) | 0.808 | 0.112 | 0.080 | 1 |

Finally, construction of Yamal 3 may be achieved by 2030 as well (Variant 2), the results are for K = {R,U,B}, $x_B^*$ = 86 bcm/a, $x_U^*$ = 67.7 bcm/a, $x_N^*$ = 0 bcm/a, $p^*$ = 138.72 $/tcm, $\Pi_{R,U,B}^*$ = 18,674 mn.$. For the case K = {R,U}, one has $x_U^{**}$ = 120 bcm/a, $x^{**}_N$ = 33.02 bcm/a, $p^{**}$ = 139.27, $\Pi^{**}_{R,U}$ = 18,606 mn.$. The coalition K = {R,B} yields $x^{***}_B$ = 86 bcm/a, $x_N^{***}$ = 55 bcm/a, $p^{***}$ = 148.75 $/tcm, $\Pi^{***}_{R,B}$ = 18,486 mn.$, while for K = {R} one obtains $x_N^{\circ}$ = 55 bcm/a, $p^{\circ}$ = 216.6 $/tcm, $\Pi_R^{\circ}$ = 10,893 mn.$. The resulting bargaining power values are entered in Table 5. Compared to Table 4, the increase of Russia's bargaining power is minimal. Therefore, it is doubtful that Russia will in fact construct the expanded variant of Yamal 3.

**Table 5:** Bargaining power (2030, Variant 2)

| | Russia | Ukraine | Belarus | Sum |
|---|---|---|---|---|
| **Bargaining power** (Shapley value) | 0.859 | 0.072 | 0.069 | 1 |
| **Bargaining power** (Banzhaf value) | 0.811 | 0.096 | 0.093 | 1 |

## 6.4.2 Results for the non-cooperative module

This section based on the same demand and cost parameters as before. The additional problem is to translate Russia's bargaining power ($P_R$, obtained from the Banzhaf value, say) into the indicator of bargaining power ($\sigma$) appearing in eqs. (13) and (14). For $P_R \rightarrow 1$, (maximum bargaining power for Russia), $\sigma \rightarrow -\infty$, while for $P_R \rightarrow 0$, $\sigma \rightarrow -1$. The non-cooperative scenario can only arise if $0 < P_R < 1$. If $P_R = 0$, Russia has no bargaining power at all, whereas if $P_R = 1$, it has all the bargaining power. In the first case, it is constrained to cooperate, while in the second case, it can force the others to cooperate. Hirschhausen v. et al. (2005) calibrate σ to –8.13953 for a year when $P_R = 0.5$ and Ukraine is the only transit country. With this information, one can map Russia's bargaining power $P_R$ into σ, using

$$\sigma = \frac{16.56298716^{P_R}}{1-P_R}(-1). \tag{41}$$

### 6.4.2.1 Postdictions for 2004

Russia's bargaining power for the year 2004 is σ = –11 according to eq. (41). Moreover, $x_N = 0$, since NEGP does not exist yet. Other parameters and the results for K = {R,U,B} are taken from the cooperative module expounded in section 6.4.1 (see Table A.1). The respective formulas from section 6.3.2 can be used to calculate the outcomes of the different coalitions. The results are presented in Table 6. The postdicted total amount of gas is lower than the actual flows measured in 2004. This is because the demand function was estimated for earlier years, neglecting the increase in demand that had occurred in the meantime. By shifting the demand function outward, resulting in b = 192, the simulation results could be made to match actual observations. However, the main findings of the simulation are not modified by these changes, and therefore b = 141.1 is retained (see Table A.1).

**Table 6:** Postdictions for 2004 (annual values)

| 2004 | (R\U\B) (1) | ({R,U}\B) (2) | ({R,B}\U) (3) | (R\{U,B}) (4) | {R,U,B} (5) |
|---|---|---|---|---|---|
| $x_U$ (bcm) | 52.33 | 76.33 | 52.34 | 54.21 | 58.37 |
| $x_B$ (bcm) | 20 | 2.04 | 20 | 20 | 20 |
| $x_N$ (bcm) | - | - | - | - | - |
| p ($/tcm) | 84.03 | 79.27 | 84.03 | 82.55 | 79.27 |
| $t_U$ ($/tcm) | 9.9 | 5.14 | 9.9 | 8.33 | 5.14 |
| $t_B$ ($/tcm) | 6.59 | 4.96 | 4.77 | 8.33 | 4.77 |
| $\Pi_R$ (mn. $) | 4,539 | - | - | 4,595 | - |
| $\Pi_U$ (mn. $) | 249 | - | 249 | - | - |
| $\Pi_B$ (mn. $) | 36 | 0.5 | - | - | - |
| $\Pi_K$ (mn. $) | - | 4,846 | 4,575 | 244 | 4,853 |
| **Σ Π (mn. $)** | 4,824 | 4,846 | 4,824 | 4,839 | 4,853 |

As standard economic theory suggests, the largest amount of gas is transported when all players cooperate, avoiding double marginalization along the supply chain. Indeed, both $x_U$ and $x_B$

attain their maximum value and price its minimum [see column (5) of Table 6]. Also, the sum of profits is maximum in the case of the comprehensive coalition (4,853 mn. $ annually). Thus, consumers get the most gas at the lowest price, while the producer-transporter coalition reaps the highest profit. The opposite situation prevails when every player is on its own and no cooperation is achieved [see column (1)]. However, differences in the total profit are small, suggesting that co-operation is not very lucrative. Moreover, the transit countries make a smaller profit when they form a coalition [compare col. (4) with cols. (2) and (5) of Table 6]. This is a result of the uniform transit fee and Russia's high bargaining power combined with its Stackelberg leader position. A coalition between the transit countries is therefore not predicted for the time of writing (2007).

Nash equilibria (NE) are displayed in Table 7. The first entry represents the payoff to Russia, the second, to Ukraine, and the last one, to Belarus. The base scenario is where all players choose to be non-cooperative, with payoffs {4,539, 249, 36}. Whenever Russia is part of a coalition, it is assumed to get all the profit and to pay shares $S_i$ to its coalition partners, providing an incentive to form the coalition. The $S_i$ value depends on the player's outside option (associated with not cooperating), which varies with the constellation. The assumption is that offer $S_i$ that exceeds the player's outside option will be accepted and cooperation achieved. If the coalition consists only of the transit countries, Ukraine is assumed to receive the whole profit, ceding a share to Belarus. It could also be the other way round without affecting the final outcome.

**Table 7:** Payoff matrix and Nash equilibria for 2004

| **Russia cooperative** | | **Belarus** | |
|---|---|---|---|
| | | cooperative (c) | non-cooperative (nc) |
| **Ukraine** | cooperative (c) | $\underline{4{,}853-S_U-S_{B1}}$ ; $\underline{S_U}$ ; $\underline{S_{B1}}$ | $\underline{4{,}846-S_U}$ ; $\underline{S_U}$ ; 0.5 |
| | non-cooperative (nc) | $4{,}575-S_{B2}$ ; 249 ; $\underline{S_{B2}}$ | $\underline{4{,}539}$ ; 249 ; 36 |

| **Russia non-cooperative** | | **Belarus** | |
|---|---|---|---|
| | | cooperative (c) | not cooperative (nc) |
| **Ukraine** | cooperative (c) | 4,595 ; $244-S_{B2}$ ; $\underline{S_{B2}}$ | 4,539 ; $\underline{249}$ ; 36 |
| | non-cooperative (nc) | $\underline{4{,}539}$ ; $\underline{249}$ ; $\underline{36}$ | $\underline{4{,}539}$ ; $\underline{249}$ ; $\underline{36}$ |

Underlined payoffs represent the player's best response to the other players' choices. There are three NE in pure strategies. Russia and Ukraine would prefer the NE with (c,c,c), because they would get a higher payoff than in the (nc,nc,nc) benchmark scenario, whereas Belarus would be better off in the (nc,c,nc) NE. One might argue that Russia, being an essential player with the dominating power, can establish the cooperative NE by offering $S_U > 249$ and $S_{B1} > 0.5$. But Belarus then could try to establish the non-cooperative NE by offering Ukraine a share of its own profit, inducing it to be non-cooperative. Yet Belarus could offer a maximum payment of a mere 35.5 = 36 – 0.5 to Ukraine without being worse off itself, while Russia could offer Ukraine up to 64.5 = 4,853 – 249 – 0.5 – 4,539 for cooperation, thus always outbidding Belarus. Therefore the cooperative NE is far more likely to obtain than the non-cooperative NE. Still, the fact that Belarus prefers the non-cooperative NE results in a higher effective payment to Ukraine. Russia has to offer $S_U > 284.5 = 249 + 35.5$ to make sure that Ukraine will cooperate and not be forestalled by an offer from Belarus. Therefore, Russia's side payments that suffice for establishing the grand coalition are $S_U = 284.5 + \omega$ and $S_{B1} = 0.5 + \omega$, with $S_U + S_{B1} < 314 = 4{,}853 – 4{,}539$ to make sure that Russia is better off as well, and $\omega > 0$ any small number.

### 6.4.2.2 Predictions for 2010

The total amount of gas shipped in this simulation (some 128 bcm/a, see sum of top three rows of Table 8) squares quite well with the amount predicted by IEA (see section 6.2.4). However, it is remarkable that the profits going to Ukraine and Belarus ($ mn. 178 and 35, respectively) are lower than in 2004 ($ mn. 249 and 36, see Table 6, col. 1), although both countries expanded their transit capacities. This can be explained by the increase in Russia's bargaining power thanks to completion of the NEGP. With its own transport route, Russia changes from an essential player to a dictatorial one. While Russia clearly is the big winner, the transit countries hardly profit from the increase in demand.

A coalition including Russia and Ukraine again is profitable [see cols. (2) and (5) of Table 8], whereas a coalition comprising Russia and Belarus is without extra benefit. Cooperation between Russia and Ukraine produces the second-highest total profit, which makes sense because Ukraine is still the low-cost provider of most transit capacity.

Table 9 presents the payoffs for the year 2010. The NE are the same as for 2004. Belarus again prefers the two cooperative NE and would therefore offer Ukraine a payment up to 32 = 35 - 3 for not cooperating with Russia. Thus, Russia's offers ensuring cooperation of the other players are $S_U > 210$ and $S_{B1} > 3$, or more generally $S_U = 210 + \omega$ and $S_{B1} = 3 + \omega$, with $S_U + S_{B1} < 252$. These side payments guarantee that the cooperative rather than the non-cooperative NE is achieved.

**Table 8:** Predictions for 2010 (annual values)

| 2010 | (R\U\B) (1) | ({R,U}\B) (2) | ({R,B}\U) (3) | (R\{U,B}) (4) | {R,U,B} (5) |
|---|---|---|---|---|---|
| $x_U$ (bcm) | 67.52 | 120 | 67.52 | 68.55 | 98.37 |
| $x_B$ (bcm) | 30 | 8.19 | 30 | 30 | 30 |
| $x_N$ (bcm) | 27.5 | 0 | 27.5 | 27.5 | 0 |
| p ($/tcm) | 121.36 | 118.85 | 121.36 | 120.55 | 118.72 |
| $t_U$ ($/tcm) | 7.78 | 5.14 | 7.78 | 6.88 | 5.14 |
| $t_B$ ($/tcm) | 5.94 | 5.09 | 4.77 | 6.88 | 4.77 |
| $\Pi_R$ (mn. $) | 12,760 | - | - | 12,795 | - |
| $\Pi_U$ (mn. $) | 178 | - | 178 | - | - |
| $\Pi_B$ (mn. $) | 35 | 3 | - | - | - |
| $\Pi_K$ (mn. $) | - | 13,001 | 12,795 | 182 | 13,012 |
| $\Sigma\,\Pi$ (mn. $) | 12,973 | 13,004 | 12,973 | 12,977 | 13,012 |

**Table 9:** Payoff matrix and Nash equilibria for 2010

| Russia cooperative | | Belarus: cooperative (c) | Belarus: non-cooperative (nc) |
|---|---|---|---|
| Ukraine | cooperate (c) | $\underline{13{,}012-S_U-S_{B1}}$ ; $\underline{S_U}$ ; $\underline{S_{B1}}$ | $\underline{13{,}001-S_U}$ ; $\underline{S_U}$ ; 3 |
| Ukraine | non-cooperate (nc) | $12{,}795-S_{B2}$ ; 178 ; $\underline{S_{B2}}$ | $\underline{12{,}760}$ ; 178 ; 35 |

| Russia non-cooperative | | Belarus: cooperative (c) | Belarus: non-cooperative (nc) |
|---|---|---|---|
| Ukraine | cooperative (c) | 12,795 ; $182-S_{B2}$ ; $\underline{S_{B2}}$ | 12,760 ; $\underline{178}$ ; 35 |
| Ukraine | non-cooperative (nc) | $\underline{12{,}760}$ ; $\underline{178}$ ; $\underline{35}$ | $\underline{12{,}760}$ ; $\underline{178}$ ; $\underline{35}$ |

### 6.4.2.3 Predictions for 2030

As mentioned in section 6.4, there are two different scenarios for 2030 (see Table A.1 for parameter values).

For the year 2030, the quantity of gas derived from the simulation and the IEA forecast are again quite close. Also, the grand coalition produces the highest total profit and the non-cooperative constellation, the lowest. The profit of a coalition between Russia and Belarus again exceeds the sum of their non-cooperative profits; in contrast to earlier years, however, the increment does not approach zero [compare cols. (1) and (3) in Tables 6 and 8] because Belarus has increased its capacity, resulting in cost savings. For the same reason, a transit coalition formed by Ukraine and

Belarus now turns profitable [compare cols. (1) and (4) of Table 6]. Although Ukraine continues to have the largest capacity, its profit decreases due to Russia's higher degree of independency and thus bargaining power.

**Table 10:** Predictions for 2030

| 2030 (1) | (R\U\B) (1) | ({R,U}\B) (2) | ({R,B}\U) (3) | (R\{U,B}) (4) | {R,U,B} (5) |
|---|---|---|---|---|---|
| $x_U$ (bcm) | 44.15 | 120 | 39.71 | 39.6 | 95.7 |
| $x_B$ (bcm) | 53.46 | 33.11 | 58 | 58 | 58 |
| $x_N$ (bcm) | 55 | 0 | 55 | 55 | 0 |
| p ($/tcm) | 139.6 | 139.19 | 139.51 | 139.6 | 138.72 |
| $t_U$ ($/tcm) | 6.02 | 5.14 | 5.93 | 5.92 | 5.14 |
| $t_B$ ($/tcm) | 5.83 | 5.43 | 4.77 | 5.92 | 4.77 |
| $\Pi_R$ (mn. $) | 18,505 | - | - | 18,504 | - |
| $\Pi_U$ (mn. $) | 39 | - | 31 | - | - |
| $\Pi_B$ (mn. $) | 57 | 22 | - | - | - |
| $\Pi_K$ (mn. $) | - | 18,633 | 18,571 | 98 | 18,664 |
| $\Sigma\ \Pi$ (mn. $) | 18,601 | 18,654 | 18,602 | 18,602 | 18,664 |

As Table 11 shows, there are only two NE left, viz. the fully cooperative and the fully non-cooperative. The third NE disappears because the transit coalition K = {U,B} now turns profitable. But against Russia, this coalition fails to be a NE, since Russia prefers the grand coalition. Indeed, K = {R,U,B} gives Russia enough payoff to be able to motivate Ukraine and Belarus to cooperate.

**Table 11:** Payoff matrix and Nash equilibria for 2030 (Variant 1)

| Russia cooperative | | Belarus: cooperative (c) | Belarus: non-cooperative (nc) |
|---|---|---|---|
| Ukraine | cooperative (c) | $\underline{18{,}664 - S_{U1} - S_{B1}}$ ; $\underline{S_{U1}}$ ; $\underline{S_{B1}}$ | $\underline{18{,}633 - S_{U2}}$ ; $\underline{S_{U2}}$ ; 22 |
| | non-cooperative (nc) | $\underline{18{,}571 - S_{B2}}$ ; 31 ; $\underline{S_{B2}}$ | $\underline{18{,}505}$ ; 39 ; 57 |

| Russia non-cooperative | | Belarus: cooperative (c) | Belarus: non-cooperative (nc) |
|---|---|---|---|
| Ukraine | cooperative (c) | 18,504 ; $\underline{98 - S_{B2}}$ ; $\underline{S_{B2}}$ | 18,505 ; $\underline{39}$ ; 57 |
| | non-cooperative (nc) | 18,505 ; 39 ; $\underline{57}$ | $\underline{18{,}505}$ ; $\underline{39}$ ; $\underline{57}$ |

While no coalition with Russia and only one transit country is more profitable than the grand coalition, the outsider would always want to offer the other transit country a payment sufficient to win it over. However Russia can outbid the outsider; specifically, the conditions for achieving the grand coalition are, $S_{U1} > 39$, $S_{B1} > 57$, and $98 < S_{U1} + S_{B1} < 160$.

**Table 12:** Predictions for 2030 (Variant 2)

| 2030 (2) | (R\U\B) (1) | ({R,U}\B) (2) | ({R,B}\U) (3) | (R\{U,B}) (4) | {R,U,B} (5) |
|---|---|---|---|---|---|
| $x_U$ (bcm) | 44.05 | 120 | 28.35 | 11.63 | 67.7 |
| $x_B$ (bcm) | 53.58 | 33.13 | 86 | 86 | 86 |
| $x_N$ (bcm) | 55 | 0 | 38.66 | 55 | 0 |
| p ($/tcm) | 139.57 | 139.18 | 139.27 | 139.57 | 138.72 |
| $t_U$ ($/tcm) | 5.99 | 5.14 | 5.63 | 5.9 | 5.14 |
| $t_B$ ($/tcm) | 5.81 | 5.41 | 4.77 | 5.9 | 4.77 |
| $\Pi_R$ (mn. $) | 18,507 | - | - | 18,506 | - |
| $\Pi_U$ (mn. $) | 38 | - | 16 | - | - |
| $\Pi_B$ (mn. $) | 56 | 21 | - | - | - |
| $\Pi_K$ (mn. $) | - | 18,633 | 18,616 | 106 | 18,674 |
| $\Sigma\ \Pi$ (mn. $) | 18,601 | 18,654 | 18,631 | 18,613 | 18,674 |

For the second variant of the scenario 2030, see again Table A.1 for parameter values. The left-hand side of Table 12 shows that total profit is again maximum when all players cooperate [col. (5] and is minimum when they fail to do so [col. (1)].

**Table 13:** Payoff matrix and Nash equilibria for 2030 (Variant 2)

| Russia cooperative | | Belarus cooperative (c) | Belarus non-cooperative (nc) |
|---|---|---|---|
| Ukraine | cooperative (c) | $\underline{18{,}674–S_{U1}–S_{B1}}$ ; $\underline{S_{U1}}$ ; $\underline{S_{B1}}$ | $\underline{18{,}633–S_{U2}}$ ; $\underline{S_{U2}}$ ; 21 |
| Ukraine | non-cooperative (nc) | $\underline{18{,}616–S_{B2}}$ ; 16 ; $\underline{S_{B2}}$ | $\underline{18{,}507}$ ; 38 ; 56 |

| Russia non-cooperative | | Belarus cooperative (c) | Belarus non-cooperative (nc) |
|---|---|---|---|
| Ukraine | cooperative (c) | 18,506 ; $\underline{106–S_{B2}}$ ; $\underline{S_{B2}}$ | 18,507 ; $\underline{38}$ ; 56 |
| Ukraine | non-cooperative (nc) | 18,507 ; 38 ; $\underline{56}$ | $\underline{18{,}507}$ ; $\underline{38}$ ; $\underline{56}$ |

#### 6.4.2.4 Strategy analysis

As shown in the preceding subsections, the grand coalition is a NE, constituting the dominant solution for rational players under stated assumptions. It is Pareto-efficient since no player can increase its payoff without diminishing that of another player. Cooperation is also the dominant strategy in a repeated game, provided the discount rate is zero or the same for all players. Differing discount rates would affect the bargaining power of the players over time, possibly resulting in changed strategies.

As can be seen from Tables 8 and 9, the opening of the first NEGP by 2010 has an enormous effect on Russia's profit. However, the increase in capacity thanks to the second pipeline still brings significant additional payoff (see Tables 10 and 12). Thus, Russia's strategy of continuously developing and increasing its own transport capacity is very lucrative. Because in the grand coalition NEGP is not used at all, the question arises whether its construction makes sense. Yet without this addition to capacity, Russia's bargaining power would be less. This in turn would require higher side payments for establishing the grand coalition, resulting in reduced profits. Also, it is questionable whether the mere threat of building the NEGP would lead to the same outcomes, its credibility being limited in view of long construction time. However, construction of the first NEGP pipeline probably cannot be stopped anymore. This could be seen as a sufficiently strong commitment for rendering the threat of adding the second pipeline credible and letting Russia still benefit from an increase of its bargaining power.

Moreover, it is rational for Russia to encourage Belarus to increase its capacity. The logic is that Belarus has the lowest marginal cost of operation, which determines the transit fee charged. This serves to minimize shipping cost to Russia. Another important factor is that an increase in the capacity of Belarus serves to weaken Ukraine's position as the main transit country at least to a certain point, lowering the value of Ukraine's outside options and making it less costly for Russia to achieve the grand coalition.

The strategy of Belarus to continuously increase its transit capacity results in increasing payoffs. It is the only way to substantially profit from the gas transit game with favorable prospects attracting foreign investors to finance the projects. Even Russia is interested in an increase of Belarus' capacity and would presumably act in its favor. Yamal 1 already has been built on Russia's initiative and financial support. On the other hand, Belarus tries hard to maintain control over its transit pipelines to Russia. Any extension of its capacity would mainly cut into Ukraine's profit, adding to existing tension between the two countries.

## 6.5 Summary and conclusion

The emergence of independent transit countries in the Eurasian gas chain has forced Russia to reassess its options. Specifically, Ukraine and Belarus have been trying to capitalize on their strategic transit position, hiking up transit fees while failing to pay their gas bills. Russia in turn is reluctant to pay high transit fees to "its former provinces". It seeks to attain autarky with regard to its gas transports by means of the Northern European Gas Pipeline (NEGP) by foreclosing competition to Blue Stream by buying up the gas from the Caspian region. This paper analyzes the decision-making situation of Russia, Ukraine, and Belarus, applying both cooperative and noncooperative game theory. The cooperative module shows that the building of transport routes under its exclusive control boosts Russia's bargaining power vis-à-vis the two transit countries in all coalitions, enabling it to siphon off future profits from an increasing demand for gas. Using side payments, it is predicted to have the capability of establishing the grand coalition (comprising all the three countries considered). Ukraine turns out to be the big loser, its bargaining power and profits continuously decreasing during the next two decades. It does not have the option of increasing its transit capacity, as the predicted outcome of the non-cooperative module is that this capacity will remain idle. Russia is building at least the first pipeline of the NEGP project. The only viable alternative for Ukraine is to cooperate, upgrading its pipeline system in order to reduce its marginal cost and to gain a competitive edge over Belarus. In all, the game-theoretic analysis performed in this paper leads to the prediction that Russia will succeed in forging the grand coalition comprising all the three countries studied here. The grand coalition is also the only Pareto-efficient Nash equilibrium of the gas transit game, offering maximum payoff to each player, with side payments sufficient for its creation and maintenance. Even for the consumers in Western Europe, the grand coalition is a favorable outcome because it delivers a maximum amount of gas at the lowest price.

A few caveats need to pointed out, however. First, the analysis performed is purely economic. In reality, the gas transit game also involves geopolitical and military interests. The gas companies are not independent from their governments, and they are often used to pursue political objectives. Second, there exist no formal enforcement mechanisms for international contracts. As seen in 2006, transit countries can breach agreements without having to fear hard sanctions. Indeed, breach of contract constitutes a big threat to all sides of any gas transit agreement, at least until construction of the NEGP is completed. Afterwards, the hold-up problem will rapidly lose importance for Russia. Nevertheless, gas flows were never interrupted for a longer period of time. This speaks in favor of a certain dominance of economic over political objectives. Indeed, the likelihood of such an interruption is small, since Russia can put enormous pressure on transit countries, who depend on Russia in many ways. Therefore, the economic analysis performed here is useful to understand the impacts of future changes on the gas chain. Various scenarios can be simulated, using published forecasts to predict outcomes in terms of prices, quantities of gas according to route, and profits accruing to companies and respective governments. Of course, the quality of these predictions crucially depends on the accuracy of these estimates.

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# Appendix

**Table A.1** Parameter values used in text

| | Symbol | 2004 | 2010 | 2030 | |
|---|---|---|---|---|---|
| | | | | Variant 1 | Variant 2 |
| Ukraine capacity,bcm/a | $C_U$ | 100 | 120 | 58 120 | 86 120 |
| Belarus capacity, bcm/a | $C_B$ | | | | |
| NEGP capacity | $C_N$ | - | 27.5 | 55 | 55 |
| Russia's bargaining power | $\sigma$ | -11.00 | -25.62 | -50.32 | -51.55 |
| $X_B$ where $MC_B = MC_U = 5.14$ | - | 2.04 | 4.74 | 9.31 | 9.95 |
| $X_B$ where $MC_B = MC_U = MC_N = 6.24$ | - | - | 18.83 | 36.99 | 37.89 |
| $X_U$ where $MC_B = MC_U = MC_N$ | - | - | 14.09 | 27.68 | 28.35 |
| Russian MC, $/tcm | $c_R$ | 12.3 | 12.3 | 12.3 | 12.3 |
| Ukraine MC, $/tcm | $c_B$ | 4.77 | 4.77 | 4.77 | 4.77 |
| Belarus MC, $/tcm | $c_U$ | 18.54 | 18.54 | 18.54 | 18.54 |
| NEGP MC, $/tcm | $c_N$ | | | | |
| Slope of demand function | a | -0.789 | -0.789 | -0.789 | -0.789 |
| Constant of demand function | b | 141.1 | 220.0 | 260.0 | 260.0 |

# Chapter 7

# Conclusions

This chapter briefly outlines key conclusions and policy recommendations that can be drawn from the presented essays, followed by some suggestions for future research.

The objective of the first essay in chapter 2 was to determine the efficient frontiers of electricity generation in the United States and Switzerland, taking into account their implications in terms of security of supply. Expected returns are defined as kWh of electricity per U.S. Dollar in levels, which amounts to adopting the so-called user view. As is true for the first four essays, the seemingly unrelated regression estimation (SURE) method was adopted for estimating the covariance matrix used in determining efficient portfolios, because the error terms of the expected return regressions are correlated. One could argue that for a population as risk-averse as the U.S. and particularly the Swiss (Szpiro, 1986), the minimum variance (MV) portfolio is the appropriate one. For that reason, efficient portfolio recommendations in this chapter are limited to the MV case only. The feasible electricity generation mix for the United States contains 60 percent *Coal*, 30 percent *Gas*, and 10 percent *Oil*, but no *Nuclear* power. Therefore current users in the U.S. are advised to substitute *Nuclear* power mainly with more *Gas* (up 12 percentage points) and *Oil* electricity (up 7 percentage points). However, although this generation mix minimizes volatility, concentration measures such as Shannon-Wiener and Herfindahl-Hirschman indices suggest that power generation technologies (and with them, supplies of primary energy sources) are not sufficiently diversified. The MV portfolio for Switzerland comprises 40 percent *Nuclear*, 32 percent *Storage hydro*, 24 percent *Run of river*, and 4 percent *Solar*, which is identical to the actual generation mix as of 2003 (AP2003). In addition, the Shannon-Wiener index shows a degree of diversification that is regarded as being secure. Thus, Swiss utilities appear to generate electricity efficiently and security of supply is not at risk. Consequently, no immediate changes appear recommendable.

Chapter 3 pursues the same objective as chapter 2 in terms of determining efficient electricity-generating portfolios, however, rather than using a user view, an investor view was adopted (changes of kWh per U.S. Dollar). Risk-averse investors in the United States are thus best advised to adopt a feasible MV portfolio comprising 60 percent *Coal*. This figure is identical to the user portfolio outlined in the preceding chapter. However, *Gas* should be replaced almost entirely (down to 1 percent). *Nuclear*, *Oil* and *Wind* should contribute 25 percent, 9 percent, and 5 percent, respectively (note, *Nuclear* and *Wind* did not contribute to the feasible MV portfolio adopting a user view). A similar picture emerges for Switzerland, where investors are advised to take identical shares of *Storage hydro* and *Solar* as in the user portfolio (32 and 4 percent, respectively), however, *Run of river* should be phased out and substituted by more *Nuclear* power (up from 40 to 64 percent). Therefore, depending on the adopted view, different efficient portfolio mixes may arise. The research presented in this dissertation does not favor one view over another, because users and investors have conflicting perspectives. However, both, risk-averse users and investors do better by adopting at least 70 percent *Coal* and *Gas* in the United States and at least 76 percent *Nuclear*, *Storage hydro* and *Solar* in Switzerland.

Chapter 4 investigated the gap between the actual portfolio and the efficiency frontiers to examine the scope of efficiency improvement of U.S. and Swiss electricity-generating technology portfolios, adopting both, user and investor views. The actual portfolios of generating technologies of the United States and Switzerland are off their respective efficiency frontiers. However, risk-averse investors and risk-neutral current users in the United States are considerably closer to their efficiency frontier than their Swiss counterparts, which arguably is due to earlier and more thorough deregulation of electricity markets in the United States. Therefore, a policy recommendation of continued electricity market liberalization might be of particular interest to Switzerland which has just recently started to give large users (in excess of 100,000 kWh/year) the free choice of provider.

The objective of chapter 5 was to determine efficient electricity-generating portfolios in Switzerland in 2035. Focusing on the feasible MV portfolio again, Swiss power portfolio holders in 2035 would be best advised to adopt a technology mix containing 28 percent *Gas*, 20 percent *Run of river*, 13 percent *Storage hydro*, 9 percent *Nuclear*, and 5 percent each of *Solar*, *Smallhydro*, *Wind*, *Biomass*, *Incineration*, and *Biogas*, respectively. This mix generates more expected return, less risk, offers more security of supply and a higher return-to-risk ratio than the actual portfolio in 2000. However, this generation mix comes at the cost of higher $CO_2$ emissions. Switzerland has allocated its Kyoto emission reductions strongly in favor of transport fuels at the expense of electricity generation (IEA, 2007). This commitment now may turn out to be a stumbling block

for the attainment of a future power mix that is both efficient and secure, unless policy is addressed to increase $CO_2$ targets towards electricity generation and away from transportation.
Finally, chapter 6 analyzed the decision-making situation facing Russia, Ukraine, and Belarus, to see whether a coalition to ship gas to Western Europe is beneficial for them. Both cooperative and noncooperative game theory is applied to see whether all three countries do better by cooperating in the gas transit business. The game-theoretic analysis performed in this paper leads to the prediction that Russia will succeed in forging the grand coalition comprising Ukraine, Belarus and itself. This grand coalition is also the only Pareto efficient Nash equilibrium of the gas transit game, offering a maximum payoff to each player, with side payments sufficient for its creation and maintenance. In addition, consumers in Western Europe favor the grand coalition, as it delivers a maximum amount of gas at the lowest price. Therefore policy recommendations should seek to facilitate cooperation between Russia, Ukraine and Belarus.

Further research could usefully deal with the following issues. First, additional countries could be included in chapters 2-5, such as economies with fully liberalized electricity markets (e.g. United Kingdom, Spain, and Norway). It would be interesting to see how these countries compare to the ones presented in chapters 2-5, in particular, whether the scope of efficiency improvement shrinks even more than the semi-liberalized electricity market in the United States (Chapter 3). In addition, investments in energy technology appear irreversible, raising the issue of their optimal timing which cannot be addressed by Markowitz mean-variance theory in chapters 2-5. A promising approach in these cases is real options theory (Dixit and Pindyck, 1994) whose prescriptions might differ from those presented here. Third, rather than limiting the analyses on to electricity-generating portfolios only, a wider perspective could be adopted in chapters 2-5, including data on transportation and long-distance heating, which all play an important role in achieving a more efficient use of energy. Finally, in chapter 6 more recent data on simulated and published forecasts could be used as a sensitivity analysis to predict outcomes in terms of prices, quantities of gas according to route, and profits accruing to companies and respective governments.

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